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List of Acronym and Abbreviation

ACF	Autocorrelations Function
AR	Autoregressive
ARMA	Autoregressive Moving Average
ASCE	American Society of Civil Engineering
a_t	a value at time t in a White noise or random shock or innovation series
AWM	Adaptive Water Management
CSA	Central Statistical Agency
C_v	Coefficient of variation
D	difference
D_t	Demand at time t
E	Evaporation
EC	Electrical Conductivity
EEPCO	Ethiopian Electric Power Corporation
EFDR	Ethiopia Federal Democratic Republic
ENTRO	Eastern Nile Technical Regional Office
F	Number of failure periods
F_t	F or Fisher distribution test statistics
GDP	Gross Domestic Product
GoE	Government of Ethiopia
GTP	Growth and Transformation Plan
GWP	Global Water Partnership
H	Water surface elevation
H_1	Alternate hypothesis
HECResSim	Hydrologic Engineering Center Reservoir Simulation
H_o	Null hypothesis
i	Chronological order number
INBO	International Network of Basin organization
IWRM	Integrated Water Resources Management
JMP	Joint Monitoring program
k	Number of lags
K_{xi}	Rank of the variable x
MA	Moving Average
MDG	Millennium Development Goal

MOFED	Ministry of Finance and Economic Development
MOWR	Ministry of Water Resources
MPIDP	Megech Pumped Irrigation and Drainage Project
N, n	Sample size or total number of data in the period of analysis
NBI	Nile Basin Initiative
NTU	Nephelometric Turbidity unit
Ø	Autoregressive model coefficient
P	Precipitation
PACF	Partial Autocorrelation Function
PASDEP	Plan for Accelerated Sustained Development to End Poverty
P_s	Partial sum or net inflow
Q	Discharge
Q_g	Ground water inflow or outflow
Q_{in}	surface water inflow
R	Reliability
R/Q_{out}	Release or outflow
RACF	Residuals Autocorrelations Function
RBOs	River Basin Organizations
RIBASIM	River Basin Simulation
r_k	Lak-k autocorrelation coefficient
RPACF	Residuals Partial Autocorrelation Function
R_{sp}	Spearman rank-correlation coefficient
s^2	Sample variance
SEPTIC	Support to Enhance Privatization, Investment, and Competitiveness
S_{max}	Reservoir maximum storage capacity
S_t	Storage at time t
S_{t+1}	Storage at time t+1
S_{t-1}	Storage at time t-1
t	discrete time interval
TAC	Technical Advisory Committee
TCU	True colour unit
TDS	Total dissolved Solids
TEC	Technical Committee
t_t	Student´s t distribution test statistics

UNICEF	United Nations Children's Fund
URC	Upper Rule Curve
USACE	United State Army Corps of Engineers
V	Volume
WEAP	Water Evaluation And Planning
WRAP	Water Right Analysis Package
WRS	Water Resources Systems
WSDP	Water Sector Development Programme
WWAP	World Water Assessment Program
WWDR	World Water Development Report
X	Variable (like discharge, Lake Level etc)
$\bar{x}$	Sample mean
z_t	A value at time t obtained from the transformation of white noise by linear filter or a standardized synthetic generated value
α	Annual yield as a fraction of the mean annual inflow
β	Time series backward operator
γ	Population autocorrelation coefficient
ΔS	Change in storage
μ	Population mean
ν or v	Degree of freedom
σ	Population standard deviation
σ^2	Population variance
ψ	Linear filter model parameter

List of symbols and molecules

Ca^{++}	Calcium ion
Cl^{-}	Chloride ion
CO_3	Carbonate ion
HCO_3	Bicarbonate ion
Mg^{++}	Magnesium ion
SiO_2	Silicon dioxide

List of Dimensions

Altitude	[m asl]
Area	[km^2; ha]
Concentration	[mg/l; g/l]
Discharge	[m^3/s]
Electrical conductivity	[µS/cm]
Length	[m; Km]
Depth	[mm; m]
Mass	[mg, g, kg]
Power	[MW; GWh/y]
Temperature	[°c]
Time	[s; min; h; day; month;year]
Velocity	[m/s]
Volume	[m^3, km^3]

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Abstract

Lake Tana is one of nature's special gifts to Ethiopia with unique and diversified socioeconomic benefits. It is the largest natural reservoir in Ethiopia and the head water of Abbay (Blue Nile) basin. The Lake sub basin is endowed with good potentials of water and land resources and has been identified as one of the most important area for various socioeconomic developments by the federal democratic republic government of Ethiopia. In recognition to this some national and regional water resources projects of various kinds are being developed and the development of some more additional projects are also deemed to be realized very quickly in the near future.

However, there is a lack of appropriate water resources systems planning and management tools that assure the sustainability of current and future development endeavors in the sub basin. The sub basin hydrology and water resources systems are not well studied and documented in scientific journal articles. Thus everyone involved directly or indirectly in the management of the sub basin's water resources systems is asking about the sustainability and viability of all ongoing and envisaged development plans. There is a great fear that some of these endeavors may bring some undesirable effect which will threaten the sustainability of the sub basin's resources. In view of this an attempt is made to conceptualize the sub basin's hydrology and water resources systems problems in a simplified way, in light of the available data, by using a hypothetical equivalent catchment. Following the conceptualization a stochastic model has been fitted to the net supply of the sub basin and different synthetic net supply series were generated. The stochastic analysis shows that a first order autoregressive model and a normal distribution can adequately represent the net supply. Simulating the Lake mass balance using the synthetic generated net supply series helps to know the performance measuring indices of the Lake in various alternative development scenarios.

The modeling and simulation attempts have revealed that operating the Lake at a minimum operating level of 1784.55m asl make the Lake to offer both hydropower supply and navigations services at equal reliabilities. Besides, it is also identified that more than 10% reduction in net supply capacity of the sub basin as a result of upstream irrigation developments has a serious consequence in the reliabilities of the services offered by the Lake. The conceptualization and subsequent modeling and simulation frame works can be easily applied and used as guiding tool in the planning and management practices of the sub basin water resources systems. However, an attempt for developing a more advanced and robotic water resources systems planning and management tools are still very crucial and mandatory for the sustainable development of the sub basin's water resources systems.

1. Introduction

1.1. Overview of water resources systems planning and management

Water is nature's gift whose availability in a region is limited by climate and topography. It is a critical natural resource upon which all social and economic activities and ecosystem functions depend. The Greek philosopher Pindar said "Water is the best of all things" (Biswas, Asit K 1997). However, water as it occurs naturally falls upon the earth at variable times and locations and in uncertain magnitudes. Freshwater supplies are erratically distributed in time and space. Ethiopia's hydrology is a very good example to explain clearly the spatial and temporal variability of rainfall. Similarly water demand is also variable and not altogether predictable. The world is challenged in balancing the difference in fresh water supply and the increasing demand and managing it in a sustainable ways by providing an appropriate water resources systems planning and management tools. Even though thousands and thousands dams and other water conveyance facilities are in operation worldwide and are being built, yet there are over 768 million people in the world who do not have access to improved sources of drinking water and 2.5 billion people of the world lack access to improved sanitation services (JMP, 2013).

Water resource systems planning and management policies need to take into account the eternal variability of freshwater supplies and demands. Water Resources Systems (WRS) can be defined as a set of water resource elements linked by interrelationships into a purposeful whole (L. Votruba et al. 1988). Hence the term "WRS" comprises water resources and means of their control and transportation to water users. The complexity of water management, combined with increased uncertainty, both through socio-economic developments and climate change, makes the traditional command-and-control approach of water resources systems management less effective. Implementing appropriate water resources systems planning and management techniques are still very instrumental and key for its sustainable development. Sustainable water resources systems are those systems that are designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological integrity (ASCE, 1998). The UN secretary general, Ban Ki-Moon, has point out that "just as water is central to every aspect of life on earth, it must lie at the heart of the new vision we forget for sustainable development for the century ahead" (WWRD 2012). Addressing how we use and manage water resources is central to setting the world on a more sustainable and equitable path (WWDR 2012).Water problems of the world are neither homogenous nor constant or consistent over time. They often vary very significantly from one region to another and from one season to another and from one year to another. Solutions to water problems depends not only on water availability, but also on many factors such as policies, legal frame work, institutional capacity, socio-economic situations and others. There is no a unique solution to all water problems over the globe. Thus, adjusting management actions and directions, as appropriate, in light of new information and new objectives on the current and likely future condition is, therefore, crucial for sustainable development.

1.2. Overview of Ethiopia's water resources systems planning and management

Ethiopia is the 2nd most populous country in Africa with a population of about 86 million people (CSA 2013). It has 12 river basins with an annual runoff volume of 122 Billion cubic meters (Bm^3) of water and an estimated renewable ground water potential of 2.6 Bm^3 (MOWR 2002). The total area covered by these basins is 1.13 Million square kilometers (Mkm^2) of which 99.3 percent is a land area and the remaining 0.7 percent is covered with water bodies of lakes. The country has 3.73 Million hectars (Mha) of irrigable land and an estimate of 160 Terra Watt hours per year (TWh/y) of hydropower potential (Awulachew et al. 2007). Rainfall is the main source of Ethiopia's renewable water resources. Average annual rainfall of the country is 848 mm, varying from less than 100 mm over the Afar Lowlands in the northeast to 2,000 mm in the southwest highlands. However, rainfall in many areas of Ethiopia is highly erratic with very high rainfall intensity and extreme spatial and temporal variability.

Although Ethiopia has reasonably good water and land resources, these have neither been developed nor managed well, leaving populations vulnerable to the destructive impacts of water and climate variability, while not providing benefits from effectively harnessing the water and land resources. The country is well known with repeated and periodic drought incidence and with its lowest coverage in water related basic services. For example, in Ethiopia the proportion of population who do not have access to improved sources of drinking water and sanitation services accounts 51% and 79% respectively (JMP 2013). Ethiopia's primary water resource management challenges are its extreme hydrological variability and seasonality. Variability is most obviously manifested in endemic and devastating droughts. Such variability mainly increases the demand for infrastructure development and the need to manage both water demand and supply. Therefore, given extreme temporal and spatial variability of meteorological and hydrological variables in Ethiopia, it is very indispensable to give significant attention to enhance better water control, use and management practices that will stimulate and accelerate the agricultural based development and hence to improve quality of life of the citizens. However, it is estimated that artificial reservoir storage in Ethiopia is about 43 cubic meters per capita in contrast to 750 cubic meters per capita in South Africa (World Bank, 2006). This indicates that there is an urgent need to go a long way in improving the level of water controlling infrastructures and land utilization so as to use the available fresh water and land resources effectively to improve the livelihood of millions in the country.

However, there are increasing efforts by the Ethiopian Federal Democratic Republic (EFDR) government to develop the water resources of the country. Unlike in the previous times currently there are numbers of dams with significant storage capacity that are under construction for hydropower and irrigation projects in some of the major basins such as Abbay, Tekeze, Awash, and Omo Gibe. Among these dams the renaissance dam, which has a storage capacity of 74Bm^3 and an installed power generation capacity of 6000MW, is the biggest that will significantly improve the energy supply capacity of the country. The construction of this dam has started on April, 2011 and expected to be completed in 2017. The dam is constructed on Abbay (Blue Nile) river which is one of the major tributary to Nile River. Completion of these dams will have a significant effect on one side in improving the power supply production capacity of the country and on the other side in improving the institutional capacity for further sustainable water resources systems planning and management practices.

Abbay basin is one of the most important basins in Ethiopia that contributes more than 40% of the country fresh water, 67% of the hydropower potential and 40% of the agricultural products of the country. The basin contains Lake Tana sub basin in its upper reach and Beles sub basin in its lower reach. These sub basins have significant economic, environmental and cultural endowments in terms of water, land, and other related resources. The sub-basins are deemed to offer tremendous opportunities for accelerated national economic growth. Particularly with significant water, land, livestock, forest and fishery resources; a rich cultural heritage and natural assets; relatively developed urban centers; good roads and air connectivity; Lake Tana sub-basin has unique potential. This potential can serve as a stimulus for growth in multiple sectors with strong multiplier effects, particularly commercially-oriented smallholder agriculture, agro-industry, tourism, fisheries, livestock and energy resulting in improved livelihoods for the sub-basin's residents and the national economic growth (World Bank 2008). The EFDR government as part of its strategy for economic development and Millennium Development Goals (MDG) achievement has identified five growth corridors. Consequently, the government in its successive plan documents called "Plan for Accelerated and Sustained Development to End Poverty (PASDEP)", and "Growth and Transformation Plan (GTP)" has shown the focus on public investment to exploit comparative economic growth advantages located in different agro-ecological zones. Hence, Lake Tana and Beles sub basins have been identified as the first of the five proposed growth zones in the country (MoFED 2006).

1.3. Overview of Lake Tana's sub basin water resources systems

Lake Tana, which is the biggest fresh water natural reservoir in Ethiopia with a maximum depth of 14m and mean depth of 9m, is nature's special gift to Ethiopia. It is located at 11°36' N & 37° 23' E with average natural altitude of 1786m asl (meters above sea level). At similar elevation the lake has a surface area of about 3050km^2 with length of 74km & 68km width and storage volume of 29km^3. The drainage area of Lake Tana sub basin has a size of 15,320km^2. The lake is fed by six major perennial rivers namely Gilgel Abay, Reb, Gumara, Megech, Gelda, and Dirma and several seasonal streams. Abbay (Blue Nile) River is the only natural out flowing river from the lake. However, hydrology of Lake Tana sub basin is not well documented in the scientific literatures except in very few journal articles and reports that present estimate of the water balance of the Lake. Although there are still huge uncertainties associated with the hydrology of Lake Tana catchment, the hydrologic study conducted by SMEC International Pvt. Ltd. indicates that the estimated annual inflow into the lake is about 4.9 Bm^3, direct annual rainfall over the lake 3.8Bm^3, Evaporation from the lake 5Bm^3, and the Lake outflow is about 3.7 Bm^3 (SMEC 2008b). Kebede et al. (2005) have also estimated the water budget component of the lake, and make a preliminary sensitivity analysis of Lake Level and Lake Outflow to rainfall changes. Wale et al. (2009) has estimated the runoff from ungauged catchments using regionalization as 880mm per year with a water balance closure error of 5%. Rientjes et al. (2011) have also dealt with regionalization studies for the purpose of simulating Lake Tana level. But SMEC (2008b) has indicated the tricky in regionalization approach as the catchments generating the base flow and surface run off for some of the major tributaries like Gilgel Abay are not concurrent. Chebud (2009) has also tried to model the Lake stage and estimated the water balance of Lake Tana. The inflow based approaches and attempts in managing the Lake and its catchment water resources are associated with huge uncertainties which can be seen clearly in the discrepancies of values of the water balance terms estimated by various studies. The summary of these investigations is shown in appendix B1.

In line with PASDEP and GTP execution of some national and regional plans were started in the Tana and Beles sub-basins. For example 2985Million cubic meters per year (Mm^3/y) of water is transferred from Lake Tana to Belese sub basin for the purpose of generating 460MW of hydroelectric power (SMEC 2008c). The water after generating the power is also used for irrigating 75000ha of land in Beles sub basin. It is one of the best and unique nature's gifts which provide such combinations without any artificial storage. Indeed the combination is advantageous in maximizing the benefit from a unit volume of water. In addition to this, some other additional artificial storages and Dams are planned and being constructed in Tana sub basin. The construction of some of these dams such as Koga Dam which has a storage capacity of 83Mm^3 and irrigation potential of 7000ha of land is completed. The construction of another dam on Ribb River, which is one of the major tributary of the Lake, is going on for irrigating 19000ha of land. Other dams on other tributaries (Gumara and Megech rivers) of the lake are also planned to be constructed very soon. An issue that needs to be raised is that in addition to the effort being exerted in increasing the level of water storage and controlling infrastructures an attempt is also required to plan, manage and use them effectively in a sustainable manner. All plans and their operations need to be implemented in view of their likely consequences to the current and future generations and the environment. Because reservoirs are capital intensive and environmentally sensitive projects that need careful planning and management. Likewise Lake Tana sub basin water resources systems development plans needs to be based on a thorough understanding and considerations of all socioeconomic and ecological consequence.

Though Lake Tana and its sub basin are endowed with enormous potentials that give heterogeneous services and products like Transportation, Fishery, hydroelectric power generation, Irrigation, livestock development, Domestic water supply, Tourism, recreation & Heritage, great care is needed in the planning and management of its water resources systems. His Royal Highness the Prince of Orange, the Netherlands, has said "how well we manage our natural resources today will determine just how well these resources will serve our descendants and us" (Loucks 2005). Effective water resources development is widely recognized as crucial for sustainable economic growth and poverty reduction in developing countries (World Bank 2004; Grey and Sadoff 2006). However, traditional methods of planning and managing water resources systems, which tend to optimize only economic benefits, are inadequate. Planning and implementing projects based on volumetric water balance results solely is less viable in utilizing the Lake with the preservation of its social and environmental heritages. Equitable and sustainable solutions require new approaches that integrate environmental, social and economic concerns. Considering the interaction of the various segments and stresses resulting from several social, environmental, economic and institutional factors that need to be addressed in order to ensure equitable and sustainable development of the sub-basin water resources are both essential and timely. So it requires urgent actions that would assist and facilitate the decision making processes in both planning and real-time operations.

1.4. Objective of the study

Lake Tana sub basin is identified as one of the best areas endowed with good water and land resources that are suitable for various socio-economic developments which will have enormous contributions to the national and regional economic development. In recognition to this EFDR government has started huge investments in developing water resources systems of the sub basin. Though the sub basin has good potential of renewable water resources it is finite and hence need to be developed within the limit. Thus, the effort made in developing the resources should be sustainable and any decision associated with it has to be justified based on an appropriate scientific methods. Evaluating and assuring sustainable utilization of the available resources in view of alternative development scenarios is very essential and mandatory. An evaluation is crucial because the lake is important to the livelihoods of many people in the current and future generations in a number of different ways including domestic water supply, irrigation, hydropower generation, fisheries, transportation, tourism, and water for livestock, as well as reeds for boat construction. Therefore, in response to the increased rate of development in Lake Tana sub basin there is an intensified need to examine the performance and sustainability of these development endeavors.

Water resources systems performance measuring indices are receiving considerably increased attention by the scientific community. Reliability, resilience, and vulnerability indexes have been identified and used as a measure of system performance characteristics. Likewise the performance of a reservoir or reservoir systems is assessed in terms of its reliability, resilience, and vulnerability. Quantifying performance measuring indices like reliability and resilience of Lake Tana and reassessing them in light of various development scenarios and information is one of the classical problems that have not been solved yet. Besides, determining the minimum feasible operating level and developing associated operation rules are also needed. In Lake Tana Catchment the availability of hydro-meteorological data is very scanty. The absences of sufficient and reliable records of inflows to the Lake have hindered effective use of conventional approaches to assess the characteristics and performance measuring indices of Lake Tana in various development scenarios. However, this need not delay or restrict our attempt to find other alternative methods that will help us towards the creation of more sustainable water resource systems planning and management scenarios in Lake Tana sub basin. A simple method that will use the available data and will be revised and improved easily in light of new information and objectives is much more preferable and applicable. Thus, the overall objective of this research is to develop a simple method which is easier to understand and explain, require less input data and time and also easier to apply in assessing the performance measuring indices of Lake Tana in view of various alternatives water resources development scenarios. To meet this over all objectives, the research has the following specific objectives:

- To assess and model the stochastic characteristics of Lake Tana net inflow and net supply time series data.
- To assess the active volume, range, minimum operating level and safe yield of Lake Tana.
- To assess the performance measuring indices of the Lake in view of various alternative development scenarios.
- To develop operation rule curves for the Lake
- To develop simple model that can be easily applied in planning and management of Lake Tana sub basin water resources systems.

1.5. Significance of the study

The outcomes of the study are believed to be applied in improving the decision making exercises in Lake Tana sub basin water resources systems planning and management practices. Apart from its application the conceptualizations and application philosophies will have a different contribution to the scientific community and practitioners in the area of water resources systems. It helps in gaining new insight in understanding water resources problems and devising a compatible solution. It may serve as a guiding reference and testimony for advocating the advantage of having a specific approach and solutions for each local problem. The methodologies and associated results will be used as a comparison and basis for further improvements of the management of the sub basin's water resources systems.

2. Review of Literatures in Water Resources Systems Planning and Management

2.1. Introduction

Water is a unique critical natural resource upon which all social and economic activities and ecosystem functions depend. The earth is blue planet. Three quarters of it are covered with water (S.K. Jain and V.P Singh 2005). However, only three per cent of water on earth is fresh and most of this is locked in the ice caps and in deep groundwater. As a result only 0.3 percent of global water is available for human consumption (Gleick 1993). Globally or regionally the supplies and availability of freshwater either green water or blue water or both is limited and finite. Green water is the rainfall that is stored in the soil and then evaporates or is incorporated in plants and organisms. Blue water, which comprises renewable surface water runoff and groundwater recharges, is the water available in rivers lakes, reservoirs, and rechargeable groundwater (World water council 2000). It is the main source for human withdrawal and the traditional focus of water resources management. Freshwater availability in a region is limited by climate and topography. Hence, the world's fresh water resources are under increasing demand and strain by a growing number of competing interests. Increasing demand for water, higher standards of living, depletion of resources of acceptable quality, and excessive water pollution due to agricultural and industrial expansions have caused intense social and political messes. For example excessive use of water in Haromaya Lake in Ethiopia for irrigation purpose coupled with sedimentation has completely dried the Lake which was used for many years as a source of water supply for the nearby city, Harar (World Bank, 2006). The world is challenged in balancing the difference in fresh water supply and the increasing demand and managing it sustainably. Even that thousands and thousands dams are in operation worldwide and are being built, yet there are over 768 million people in the world who do not have access to improved sources of drinking water and 2.5 billion people of the world lack access to improved sanitation services (JMP, 2013). Implementing appropriate water resources systems planning and management approaches are still very instrumental and key to solve water resources related problems.

There are huge differences in the availability of fresh water resources in different parts of the world. The objective of water resources planning and management is, therefore, to provide the supplies of water in accordance with the temporal and spatial distribution of supplies and demands through water regulation and distribution systems. It is concerned with modifying the time and space availability of water for various purposes so as to accomplish certain basic objectives. This involves the identification of structural and non-structural measures. Structural measures may include diversion canals, reservoirs, hydropower plants, levees, irrigation delivery, and recreation facilities e.t.c. Non-structural measures may include land use controls and zoning, flood warning and evacuation measures, and economic incentives and disincentives that affect human behavior with regard to water and watershed use.

Planning and management of water resources systems involves identifying just what, when, and where structural and non structural measures are needed, the extent to which they are needed, and their combined economic, environmental, ecological and social impacts (Loucks, 2009). Planning and management of water resources systems is an activity that is becoming increasingly important in almost all regions of this planet to achieve environmental sustainability. However, growing water demand and misuse of fresh water pose serious threat to sustainable development. Water resource professionals have an obligation to design and manage water resource systems so that they can fully contribute to an improved quality of life for all humans. Planning for sustainable development of water resources means water conservation, waste and leakage prevention, improved efficiency of water systems, improved water quality, water withdrawal and usage within the limits of the system, a level of water pollution within the carrying capacity of the stream, and water discharge from groundwater within the safe yield of the system. Population growth, technology, changing lifestyles and increased consumption and climate change are among others that introduce uncertainty to water management. Water resources systems that are managed to satisfy the changing demands placed on them now and on into the future, without system degradation can be call sustainable.

2.2. Common approaches and practices in water resources planning and management

Water resources problems are complex in nature. Water problems of the world are neither homogenous nor constant or consistent over time. They often vary very significantly from one region to another and from one season to another and from one year to another. Solutions to water problems depends not only on water availability, but also on many factors such as policies, legal frame work, institutional capacity, socio-economic situations and others. Water demands and the management approaches needed to solve water related problems are dynamic in nature. There is no question that the future water related issues of the world are likely to be different from those that were witnessed in the past or are being encountered at present (Biswas, 2009). While historical knowledge and past experience are always useful, identifying, analyzing, and solving water problems of the future will require new insights, additional skills, innovative approaches, adaptive mindsets, and proactive institutions (Biswas, 2009). Understanding the multiple aspects and roles of water is crucial to governing it effectively (WWDR, 2102). Different water resources planning and management approaches have been exercised for many years and yet its complex nature was not capture wholly. Some of the commonly used and practiced water resources planning and management approaches are briefly described in the following sections.

2.1.1. The Sectoral approach

In the past, planning of water resource projects such as dams and their operation focused primarily on meeting future demand through identification of the least cost option. Planning and management of water resources systems were original restricted to technical and economic considerations only. Social, environmental and other factors were not considered. Project feasibility was solely based on benefit cost analysis. The approach is entirely sectoral based with no integration and coordination with other sectors and stakeholders. The traditional method, which tends to optimize only economic benefit, is inadequate. As a result of this, environmentalist and sociologist have criticized engineers for constructing concrete monuments with insufficient attention to background. Matondo (2002) pointed out that traditional water resources planning and management has failed to lead to sustainable water resources development especially in developing countries where environmental preservation has received less attention to communities who have to deal with the immediate realities of poverty. Following this comment planning ideas have been changed. Equitable and sustainable solutions to water problems require new approaches that integrate environmental, social, and economic concerns. Thorough environmental studies, social and economic studies now preceded project formulation. Justification solely on the basis of benefit cost studies is no longer sufficient for many development agencies.

2.1.2. The system approach

Water resources system consists of different elements of two distinct environments: one is the physical, chemical, and biological environment and the second is a cultural environment with social, political, economical, and technological dimensions (karasmouz et al., 2003). The physical and cultural environments are inseparable. Both hydrological and institutional considerations are important in water resources planning and management. Because of the extreme complexities of water resource problems highly simplified approaches were being practiced in solving them. However, the Harvard water Group Publication in 1962 on Design of Water Resource Systems has furnished an important impetus to the application of system analysis techniques to water resource studies. Since that time a great deal of activities in the development of systems application techniques has taken place in universities and other organization. Subsequently the application of system approach improves the basis for decision making for complex water management problems. System can be defined as a collection of various structural and non-structural elements that are connected and organized in such a way as to achieve some specific objective through the control and distribution of material resources, energy and information (Simonovic, 2009). System approach is a general problem solving technique that brings more objectivity to the engineering planning and design processes.

The system approach is a paradigm concerned with systems and interrelationships among their components. It combines knowledge of the available analytical tools, understanding of when each is most appropriate, and skill in applying them to practical problems. System approaches have great potential for providing appropriate support for effective water resources systems planning and management. System analysis involves the use of rigorous methods to help determine preferred plans and designs for complex, often large-scale, systems. Simulation (behavior analysis), optimization and multi-objective analyses are the most commonly used techniques is system analysis. Simulation may be described as the process of duplicating the essence of a system or activity with respect to some predetermined objective without actually attaining reality (Davis, C. Pat and Augustine, J. F. 1971). Simulation models play an important role in water resources assessment, planning and management. The use of simulation as a tool in studying the planning and operation of reservoir is now becomes a routine application. It is widely accepted within the water resources community and is usually designed to predict the response of a system under a particular set of conditions. Optimization is the science of choosing the best among the number of possible alternatives. The management of complex water resources systems rarely involves a single objective. So, the application of multi-objective analyses is becoming prudent in the planning and management of water resources systems. Nowadays Water resource systems planning and management is heavily relied on the application of systems approach and system analysis techniques to formulate and solve water resources management problem

2.1.3. Integrated Water Resources Management (IWRM) approach

The concept of Integrated Water Resources Management was recognized in Agenda 21 during the 1992 United Nations Conference on Environment and Development (GWP-TEC 2004). It was later proposed in the implementation plan of the 2002 World Summit on sustainable development in Johannesburg. It was identified during the United Nations World Summit in 2005 as a strategy to accomplish the United Nations Millennium Development Goals. IWRM is defined as a process that 'promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystem' (GWP, 2000). This definition of IWRM has been critically commented by Biswas (2004, 2008) as unusable or un-implementable, in operational terms. However, for balancing views and improving practices, Grigg (2008) has provided another definition of IWRM as 'a frame work for planning, organizing and operating water resources systems to unify and balance the relevant views and goals of stakeholders'. IWRM implies that all the different uses of water resources are considered together. River basin has been recognized as a practical hydrological unit for integrated water resources management. The practical application of IWRM has been described in GWP and INBO (2009).

Water allocation and management decisions should consider the effects of each use on the other, thus taking into account overall social and economic goals, including the achievement of sustainable development targets, health and safety. IWRM entails the coordination of policies, institutions, regulatory frameworks, planning, operations, maintenance and design standards of numerous agencies and departments responsible for one or more aspects of water and related natural resources management. Multi-disciplinary and multi-agency coordination and cooperation is therefore an important feature of IWRM. But given the importance of coordination and integration in water resource management the pace of its practical implementation is still very low. In developing countries, where there are limitation in institutional capacity and numbers, legal and regulatory frame works, it is hardly possible to implement all IWRM philosophies. However, as it is point out by Grigg (2008), it may be taken and applied as a framework with due consideration of its continual improvement in light of new information and institutional set up. Such application of IWRM leads to the adaptive water management approach.

2.1.4. The adaptive water management approach

The complexity of water management, combined with increased uncertainty, both through socio-economic developments and climate change, limits the efficiency and effectiveness of integrated water resources systems planning and management approaches. NeWater (New Approach to Adaptive Water Management under Uncertainty), a research project supported by the European Commission, believes that an adaptive water management approach towards IWRM responds to this. In the face of certain changes, but with uncertain impacts, an evolving and adaptive strategy for water resources development, management and use is a necessary condition for sustainable development. NeWater has defined Adaptive Water Management (AWM) as an approach that addresses uncertainty and complexity by increasing and sustaining the capacity to learn while managing (http://www.newater.uni-osnabrueck.de). It pointed out that learning is sustained by an iterative process of testing and improving methods of analysis and management policies and practices in response to insights from monitoring outcomes of implemented management strategies. Adaptive management can generally be defined as a systematic process for improving management policies and practices by learning from the outcome of management strategies that have already been implemented. It is learning to manage by managing to learn. Learning in water management encompasses the range of ecological, economical and socio-political domains in testing the effectiveness of structural and non-structural measures. Adaptive water management is a process of adjusting management actions and directions, as appropriate, in light of new information on the current and likely future condition of our total environment and on our progress toward meeting our goals and objectives (Loucks, 2000). Inflexibility in the face of new information and new objectives and new social and political environments is an indication of reduced system sustainability. This is slightly observed in the management of Nile water resources. The hydropower development attempt made by Ethiopia, the country that is found in the upstream side of the basin and contributes about 86% of Nile flow, is not positively accepted by Egypt, the most downstream country that entirely depends on Nile. This is an indication to inflexibility to new information, new social and political environments. Such inflexibility in light of new knowledge and socio-economic and environmental situation is a big threat to sustainably develop the basin's water resource systems.

Adaptive management is a process of adjusting management actions and directions, as appropriate, in light of new information on the current and likely future condition of our total environment and on our progress toward meeting our goals and objectives. Management decisions can be viewed as experiments, subject to modification - but with goals clearly in mind. Adaptive management recognizes the limitations of current knowledge and experience and we learn by experimenting. It helps us move toward meeting our changing goals over time in the face of this incomplete knowledge and uncertainty. It accepts the fact that there is a continual need to review and revise environmental and other restoration and management approaches because of the changing as well as uncertain nature of our socioeconomic and natural environments.

2.2. Water resources systems planning and management models and tools

Modeling and analysis methods for evaluating the water supply capabilities of reservoir/river systems are fundamental to the effective management of the highly variable water resource of a river basin. Almost all the freshwater available for human use originates from precipitation, that varies immensely over time and space. Such variability mainly increases the demand for infrastructure development and the need to manage water demand and supply. Allocation of limited water resources between agricultural, municipal, industrial, and environmental uses now requires the full integration of supply, demand, water quality and ecological considerations. Modeling systems provide quantitative information for use in evaluating alternative plans and water regulation policies.

A broad array of generic computer models has been developed for water resource systems planning and management. According to Wurbs (2005a) generic means that a computer model is application to a range of concerns dealing with river basin systems of various configurations and allocations rather than being site-specific customized to a particular system. The Conceptualization, theoretical justifications, and applicability of some of the most commonly practice generalized river/reservoir system simulation models such as River ware, MIKE-BASIN, MODSIM, RIBASIM, WRAP, WEAP, WBalMo, and HECResSim have been reviewed by different authors see for example (Yeh 1985; Wurbs 1993, 2005a, 2005b; Labadie 2004; Rani 2010; SEPTIC 2004). Most river/reservoir systems models are based on volume balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. They are based on a node-link network representation of the water resource system being simulated.

Many of the above mentioned models are highly applicable in multi-reservoir multipurpose systems. Problems in a single reservoir systems can be easily solved using the available classical knowledge of reservoir design and operation techniques. Selecting a modeling and analysis approach for a particular application depends upon the characteristic of the application, the analysis capabilities provided by alternative models, and the background and preferences of the analysts. Spatial variations in geography, economic development, and climate are also key considerations in water resources development and management. Although many water resources systems planning and management models have been developed in the developed countries, it is doubtful that any of these models would be completely satisfactory for use in developing nations. Differences in the physical and social environments limit their direct practical application. Customizing the models in view of the new physical and social environment is very essential to increase their amenability and dependability.

Direct application of any of the above mentioned or another similar model in Lake Tana sub basin water resources systems planning and management is limited due to lack of adequate data. An attempt to apply these models will be associated with many uncertainties resulted from data generation. Thus the authors have preferred to develop a simple model based on the available data with due understanding and consideration of the complete situations in the sub basin. The idea of equivalent catchment concept has simplified the complexity and helps in easily representing the systems in a single reservoir system. Complete descriptions of the conceptualization and methodology applied in this research are presented in chapter four.

2.3. Water Management in Reservoirs

2.3.1. Introduction

An important aspect of water resources development projects is planning and operation of reservoirs. Lakes and reservoirs are basins filled with water that is often used by humans (S.E. Jorgensen et al., 2005). Lakes and reservoirs are components of many river systems. They are typically dramatic and visually pleasing features of a watershed or basin. Lakes are naturally-formed, usually bowl-shaped, depressions in the land surface that have filled with water over time. In contrast to natural processes of lake formation, reservoirs are water bodies that are usually formed by constructing a dam across a flowing river. A dam may sometimes also be constructed at the outlet channel of a natural lake as a means of providing better control of the lake's water level (example the weir constructed at the outlet of Lake Tana in Ethiopia). Lakes and reservoirs are important sources of freshwater for agriculture, industry and municipalities. At the same time, they provide habitats for a variety of species of plants and animals. Large natural lake looks much the same as large artificial reservoir, and both often contain the word 'lake' in their name. Many features of natural lakes and artificial lakes (reservoirs) are similar and the approaches for their use and management also bear great similarity. Therefore, the authors used the Words Lake and reservoir synonymously. There are a number of artificial and natural reservoirs in the world with significant storage capacity such as Lake Nasser in Egypt with a storage capacity of 157km^3. Constructions of such huge reservoirs are capital intensive and environmentally sensitive projects that need careful planning and management.

Water as it occurs naturally falls upon the earth at variable times and locations and in uncertain magnitudes. Water demand is multipurpose, seasonally variable, and not altogether predictable. This variability in time, and location, and quantity of both supply and demand is the reason reservoirs and related development works are necessary. Reservoirs smooth out this variability by reducing high flows and increasing low flows, and generally make water available when and at the location it is needed. Using reservoir the natural streamflow can be regulated so that the outflow follows the desired pattern to match with the temporal and spatial variability of water demand. The principal function of a reservoir is, therefore, regulation of natural streamflow by storing surplus water in the high flow season to control floods and releasing the stored water in the dry season to meet various demands. Besides, a reservoir provides a water head which can be used for generation of electric power and it can also be used for flood control, navigation, and habitat for aquatic life, recreation and sport. It enhances scenic beauty, and support wild life. The storage required on a river to meet a specific demand depends on three factors; the variability of the river flow i.e. hydrology of the catchment supplying the reservoir, the size and variability of the demand, and the degree of reliability of this demand being met.

Various classifications of reservoirs are possible depending on the purpose, and the storage space available in it. Depending on it purpose a reservoir may be classified as a single purpose or multipurpose. A single purpose reservoir serves only one purpose such as supplying water for domestic consumptions, irrigation, or for hydropower generation. A multipurpose reservoir serves a combination of these purposes. Based on the storage space provided, two general classes of reservoir systems exist: over-year (alternatively known as carry-over) and within-year systems. Within-year systems are characterized by reservoirs which typically refill at the end of each year. Such systems are particularly sensitive to seasonal and even daily variations in both the hydrological inflows and the system yield. Over-year systems do not typically refill at the end of each year. Water supply failures for within-year systems tend to be short-lived in comparison with over-year systems since within-year systems tend to refill on an annual basis. Here a failure is defined as the inability of a reservoir system to provide the contracted demand in a given year. Naturally, most reservoir systems exhibit some combination of over-year and within-year behavior. Management of reservoir involves the assessment of storage-yield-reliability relationships and development of associated operation rules.

2.3.2. Storage-Reliability-yield relationships

Effective management of water resources of a river basin requires an understanding of the amount of water which can be abstracted and supplied under various conditions. The determination of storage-yield relationships for a reservoir is one of the basic hydrologic analyses associated with the design of water resource systems. Basically, there are two ways of viewing the storage-yield relationship. The most common viewpoint requires the determination of the storage required at a given site to supply a given yield with a stated reliability. This type of problem is usually encountered in the planning and early design phases of a water resources development study. The second viewpoint is used to reassess the water demand which can be satisfied by existing reservoirs. This often occurs in the final design phases or in re-evaluation of an existing project for a more comprehensive analysis.

The amount of water which can be supplied by a stream/reservoir system may be analyzed in terms of a firm or dependable yield, percent of time specified quantities of water are available, reliability of meeting various demand level, risk of shortages, likelihood of various reservoir storage levels occurring, or a tabulation of the amount of water available during each period based on specified conditions or assumptions. Firm yield is defined as the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the hydrologic period-of-record (Wurds, R.A. and Bergman, C.E., 1990). Precise definition of firm yield and reliability can be formulated for a simple river basin with a single reservoir. For a complex multiple reservoir, multiple use, river basin system, firm yield and reliability and their relationship must be defined in terms of basic assumptions and approaches used in handling various complicated factors. Understanding the storage-yield-reliability relationships are a key element in all studies and decisions involving the provision of water storage facilities.

Regulation of stochastically fluctuating flows of a natural stream by reservoir is a classical problem known for thousands of years. Many studies have been performed with many different methods and different results for the relationship between storage capacity and target demand (draft). After the birth of the classical Ripple mass curve analysis, many innovative approaches were put forth by many researchers such as Hazen (1914); Hurst (1951); Moran (1959); Klemes (1969); and Vogel and Stedinger (1987). Klemes (1987) has provided detail reviews of the history of reservoir storage yield relationship. These methods available for determining the storage yield relationship from a stream flow record may be broadly classified into sequential and non-sequential procedures (Vogel and Stedinger, 1987). Sequential analysis requires routing of the complete stream flow record or synthetic generated through the reservoir system while accounting for the necessary outflows which may include: water supply, evaporation, seepage losses, minimum downstream releases and other operations. The U.S. Army Corps of Engineers (1967; 1975) advocate the use of sequential analysis in the United States. However, the most general and widely applied methods are the Ripple mass curve and the behavior (simulation) analysis using historical and synthetic generated stream flows (McMahon and Mein 1978)).

Traditionally, most water resource engineers have employed Ripple's mass curve approach or the sequent peak algorithm in conjunction with the historical stream flow sequence to obtain a single estimate of the design capacity of a storage reservoir. Measured historical data are limited in extent and accuracy. The future is always uncertain. Consequently, reservoir related studies necessarily involve uncertainties and approximations. The stochastic nature of streamflow and other pertinent variables must be reflected in methods for quantifying yield. In view of these, more recently, stochastic stream flow models have been recommended for use in driving the probability distribution of the required capacity of a storage reservoir to maintain a specified release. The development of the field of stochastic or operational hydrology provides the analyst with a flexible tool that can be used to circumvent the shortcomings of historical records. The philosophy behind using a synthetically generated stream flow is that if many sequences of flows are used and each is statistically likely to occur and has a length equal to the operation period of interest, it is likely that the entire range of plausible future scenario will have been explored. Most importantly, synthetic generation of streamflow or other hydrological variables may be used to estimate the reliability or probability with which a storage reservoir can be deliver scheduled quantities of water. Such procedures were boldly advocated by Maass et al (1962). The uncertainties in reservoir planning and operation can be reduced by the use of synthetic hydrology and simulation. The historical streamflow is one sequence representative of what could occur in the future. The synthetically generated streamflows represent alternative sequences which have the same likelihood of occurring in the future.

Proper operation, management and design of reservoir systems requires a thorough understanding of the likelihood, duration and magnitude of potential reservoir system failure sequences which eventually lead to compute the performance measuring indices of the system. Reliability, resilience, and vulnerability indices are used as sustainability criteria and performance measures of water resources systems. They have been considered as integrated part of water resources systems analysis and design. Likewise the performance of Lake Tana has to be examined in terms of its reliability, resilience, and vulnerability. The definition of reliability, resilience, and vulnerability have been introduced by a number of previous investigators see for example Thomas Rodding Kjeldsen & Dan Rosbjerg (2004), Vogel & Bolognese (1995); Vogel et al (1999); Wurbs, R.A. and Bergman, C.E. (1990) and McMahon and Mein (1978). In general reliability provides a measure of how often a system fails or in other words it is the percentage of time that a specified demand level can be met. The measure of the ability of the system to return to non-failure state after a failure has occurred is resilience and vulnerability provides a measure of how severe failures may become. A failure is defined as the inability of reservoir system to deliver a specified yield or service. The most common definition of probability of failure is the proportion of time units or periods such as months during which the reservoir cannot meet the demand under the adopted operating rule. It is common for all estimators to rely on the statistical characteristics of failure periods for estimation.

Reliability R is an index in the range 0-1 which indicates how satisfactorily the reservoir performs, and it may be expressed as periodic or volumetric reliability. Reliability estimates can be formulated on either a periodic or a volumetric basis. Periodic reliability can be defined as the proportion of time that the system is able to meet demands. Volumetric reliability relates the volume of water supplied to the total volume of water demanded during the study period and it can be expressed as the ratio of the volume of water supplied to the volume demanded (McMahon and Mein 1978). Alternatively, reliability estimates can be formulated in terms of the likelihood that demand can be met continuously during a long multiyear period. In this case, computation would involve repeated simulations of a large number of synthetically generated equally-likely streamflow sequences of a specified length, such as 50 years (Wurds, R.A. and Bergman, C.E., 1990). The reliability (R) would be the number of sequences for which the demand is met divided by the total number of sequences.

$$R = 1 - \left(\frac{F}{N}\right) \qquad (3.1)$$

Where F is the number of failure supply period (days, months, or seasons) and N is the total period of analysis

In a given year, a reservoir system may be in either one of two states: (1) Failure state; or (2) regular operation. Here a failure state is considered one in which the stated yield or service could not be met, and a regular state is one in which the stated yield or service is provided or exceeded. The assumption of only two reservoir system states dictates that the reservoir system must be able to pass from one state to the other in any given time. Such assumption helps to understand the situation easily and clearly. However, reliability statements alone do not convey information regarding the consequences of failure (system vulnerability) or the ability of the system to recover from a failure (system resilience).

Almost all previous investigations on Lake Tana focus on estimation of the water balance terms only. There is no any study that tries to assess the performance measuring indices of Lake Tana. This study attempts to assess the performance indices of Lake Tana specially its reliability in view of various alternative development scenarios. The authors have applied simulation technique using different synthetically generated net inflow series in assessing Lake Tana's supply and navigability reliabilities.

2.3.3. Reservoir Operation and Management

Reservoir operation is an important component of water resources systems planning and management. A reservoir is operated according to a set of rules or guidelines to store and release water. The way in which releases are controlled is called the release or operating rules. Rule curves are often used in actual system operation. A rule curve or rule level specifies the desired storage to be maintained in a reservoir as closely as possible during different times of the year while trying to meet various demands. Here the implicit assumption is that a reservoir can best satisfy its purposes if the storage levels specified by the rule curve are maintained in the reservoir at different times.

A reservoir operation policy specifies the amount of water to be released from storage at any time depending on the state of the reservoir, level of demands and any information about the likely inflow to the reservoir. Usually the volume of water from a reservoir is equal to the volume of water required to satisfy various demands and losses. However, there may be periods when either the reservoir level is so low that the water required cannot be supplied or that prudence dictates that only part of the water demand is released from storage. While operating a reservoir with the help of rule curves, there are several possibilities: If the water level in the reservoir at any time is above the elevation stipulated in the rule curve at that time, releases are made to meet all demands. If the available water is in the vicinity of that indicated by the rule curve, the release of water should be restricted such that the storage does not fall appreciably below the rule level. If for some reason, the level in the reservoir is such below the rule curve, the release should be curtailed with attempts to return to the curve level at the earliest. The release decision may incorporate relative priority among various uses and incase of deficit, the higher priority demands are met first.

Efficient reservoir management requires optimal policies that manage storage and releases and aim maximize benefits. To obtain optimal rules for storage reservoirs, large numbers of simulation and optimization models have been developed over the past decades see for example Yen (1985), Labadie

(2004); Mahootchi M. et al (2010) and Rani D., Moreira M.M. (2010). The selection of appropriate model for derivation of reservoir operating rule curve is difficult and most often there is a scope for further modification as the model selection depends on data availability. Many of the information used in reservoir management optimization models are affected by stochastic uncertainty. In addition, nonlinearity, and the large scale nature of the problem makes the solution process challenging.

Yen (1985) has mentioned clearly the absence of a general optimization algorithm that can be applied to any given reservoir operation. The choice of methods depends on the characteristics of the reservoir system being considered, on availability of data, and on the objectives and constraints specified. Most of these surveys emphasis that the simulation-optimization techniques can be generally better than some other methods employed in reservoir problems. In spite of the development and growing use of optimization techniques, simulation models remain in practice a prominent tool for reservoir systems planning and management studies (Rani D., Moreira M.M., 2010). In this regard, simulation is an effective tool for studying the operation of the complex water resource system incorporating the experience and judgment of the planner or design engineer into the model. In view of this comment, the authors have applied simulation techniques in determining the operating policies or rule curves for Lake Tana.

In behavior or simulation analysis, the changes in storage content of a reservoir are calculated using the mass balance (water balance) equation and represent the hydrological behavior of reservoir systems using inflows, outflows and other operating conditions. This equation states that the sum of inflow and outflow components and the change in storage must be zero over a give time interval. The equation can be expressed as:

$$Q_{in} \pm Q_g + P - E - R - \Delta S \pm \delta = 0 \qquad (3.2)$$

Where Q_{in} is the surface water inflow into the reservoir; Q_g is the ground water inflow or outflow; P is direct precipitation; R is the release from the reservoir; E is the evaporation from the reservoir, ΔS is the change in storage, and δ is the error term. The water balance equation may be used for any time interval. The mass balance equation is also fundamental in making decisions regarding releases in different time periods which are made in accordance with the available water, inflow, and demands.

2.4. Brief review of water resources and Climate change

The Earth’s global mean climate is determined by incoming energy from the Sun and by the properties of the Earth and its atmosphere, namely the reflection, absorption and emission of energy within the atmosphere and at the surface. Changes have occurred in several aspects of the atmosphere and surface that alter the global energy budget of the Earth and can therefore cause the climate to change. Among these are increases in greenhouse gas concentrations that act primarily to increase the atmospheric absorption of outgoing radiation, and increases in aerosols (microscopic airborne particles or droplets) that act to reflect and absorb incoming solar radiation and change cloud radiative properties. The second Turn down the heat report of the world bank indicate that in the absence of further mitigation action there is a 40 percent chance of warming exceeding 4°C by 2100 and a 10 percent chance of it exceeding 5°C in the same period. Even at present warming of 0.8°C above pre-industrial level, the observed climate change impacts are serious and indicate how dramatically human activity can alter the natural environment upon which human life depends. Parry et al. (2007) have indicated that observational evidence from all continents and most oceans shows that many natural systems including water resources are being affected by regional climate changes, particularly temperature increases.

The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, evaporation, sea level and precipitation variability. Climate change affects also the function and operation of existing water infrastructure as well as water management practices. Even without any climate change, population growth alone is expected to put pressure on water resources in many regions in the future. With projected climate change, however, pressure on water resources is expected to increase significantly. The second Turn Down the Heat report of the World Bank reveal that global warming above 1.5°C to 2°C increases the risk of reduced crop yields and production losses in sub-Saharan African, South East Asia and South Asia. These impacts would have strong repercussions on food security and are likely to negatively influence economic growth and poverty reduction in the impacted region. Recent research showed that the 2011 Horn of Africa drought, particularly severe in Kenya and Somalia, is consistent with an increased probability of long-rains failure under the influence of anthropogenic climate change. Africa is particularly dependent on agriculture for food, income, and employment, almost all of it rain-fed. Under 2°C warming, larger regional risks to flood production emerge; these risks would become stronger if adaptation measures are inadequate.

By 2020, between 75 million and 250 million people are projected to be exposed to increased water stress due to climate change (Parry et al. 2007). If coupled with increased demand, this will adversely affect livelihoods and exacerbate water-related problems. Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Agricultural production, including access to food, in many African countries and regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease. This would further adversely affect food security and exacerbate malnutrition in the continent. In some countries, yields from rain-fed agriculture could be reduced by up to 50% by 2020. Local food supplies are projected to be negatively affected by decreasing fisheries resources in large lakes due to rising water temperatures, which may be exacerbated by continued overfishing. So there is no way to ignore effect of climate change on water resources systems planning and management especially in areas where such impacts are already being observed.

Though there are no sufficient studies pertaining the effect of climate change on Lake Tana sub basin water resources systems Nigatu (2013) has tried to shows that there will be an increase in the minimum and maximum values of temperature and an increase in Lake Inflow, precipitation and evaporation in some climate scenarios. In spite of the limitations in getting adequate particular studies on effects of climate change in Lake Tana sub basin future water resources systems planning and management tasks can be judged and considered based on the perspectives of the available regional climate studies.

3. Description of Water Resources Systems in the study area

3.1. General descriptions of Ethiopia's drainage basins and water resource systems

Ethiopia has 12 river basins shown in Figure 3.1. Some features of the basins are shown in Table B2 in the appendix. The total area covered by these basins is 1.13 million km² of which 99.3 percent is a land area and the remaining 0.7 percent is covered with water bodies of lakes. The total annual runoff volume and renewable ground water potential generated from these basins are estimated as 122 Billion cubic meters (Bm^3) and 2.6 Bm^3 (MOWR 2002) respectively. These alone show the physical availability of 1400m^3 per year per capita (in consideration of the 2013 population estimate of the country) share of renewable fresh water. It may appear as relatively good potential especially when it is considered with the availability of additional green water in the country. However, due to lack of water storage infrastructure and large spatial and temporal variations in rainfall, there is not enough water for most farmers to produce sufficient amount of crops per year. Rainfall is the main source of Ethiopia's renewable water resources. Average annual rainfall of the country is 848 mm, varying from less than 100 mm over the Afar Lowlands in the northeast to 2,000 mm in the southwest highlands. It is highly erratic with very high intensity and extreme spatial and temporal variability (Awulachew, Seleshi B. 2007). The mean annual temperature is 22.2 degrees Celsius. The lowest temperature ranges from 4-15 degrees Celsius in the highlands, and the highest mean temperature is 31 degree Celsius in the lowlands at the Denakil Depression (Awulachew, Seleshi B. 2007). Therefore, given extreme temporal and spatial variability of meteorological and hydrological variables in Ethiopia, it is very indispensable to give significant attention to enhance better water control, use and management practices that will stimulate and accelerate the agricultural based development and hence to improve quality of life of the citizens.

The country has 55 million ha of arable land of which 3.73 million ha can be potentially develop by irrigation. The economically exploitable hydropower potential of the country is estimated at 30000MW (ENTRO 2007). However, the total installed capacity is 2000 MW (MOFED 2010), which is less than 10 percent of the potential. The total area under irrigation in 2006 was reported to be 603,359 hectares (less than 5% of its total irrigation potential); of which traditional irrigation accounts for 479,049 hectares while 124,569 hectares of land was developed through medium and large scale irrigation schemes (MoFED, 2006). It is striking that less than 5 percent of the estimated potential 3.73 million hectares of irrigable land in Ethiopia has been developed. Recently there is, however, an effort by the EFDR government to develop irrigation mainly for sugar plantation in some of its basins such as Abay , Awash, Omo, and Tekeze. Apart from the sugar plantation, expansions of irrigation projects for crop, vegetables and fruits production are getting due attention and consideration by EFDR government in recent times.

The authors believe that these effort will bring a considerable change in the total area of irrigated land in Ethiopia in the coming few years.

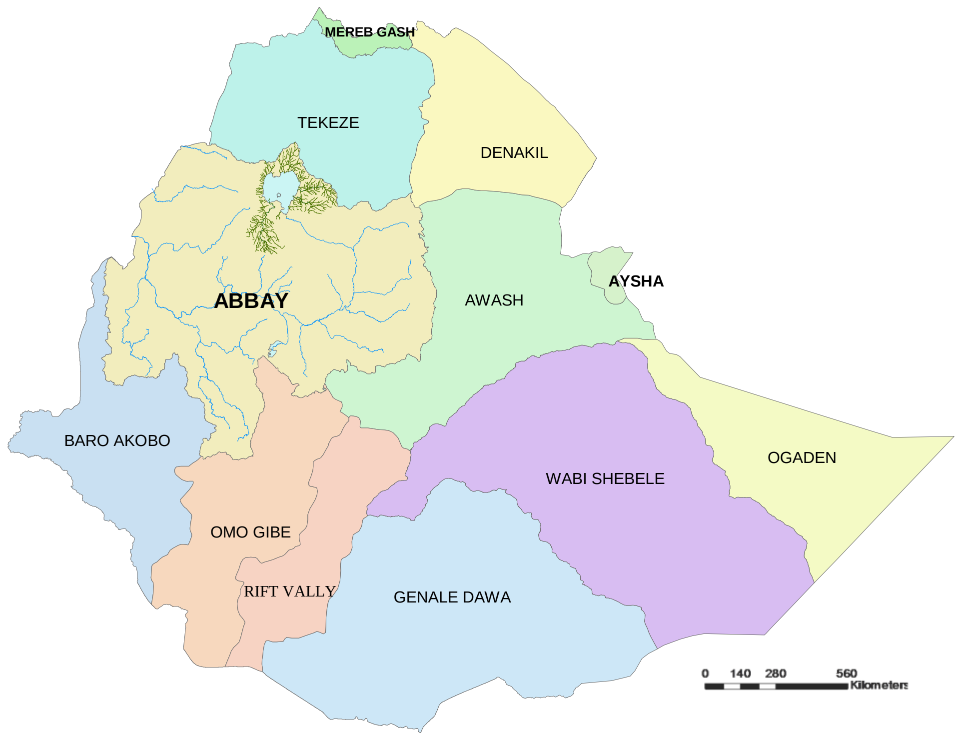


Figure 3.1 Drainage Basins of Ethiopia

Ethiopian agriculture plays a dominant role in the overall economic performance of the country, not only in terms of its contribution to GDP, but also as a major source of foreign exchange earnings, and in providing employment to a large segment of the population. Nearly 85% of Ethiopia's populations are managing their livelihoods in agriculture and related activities. The very structure of the Ethiopian economy with its heavy reliance on rain fed subsistence agriculture makes it particularly vulnerable to hydrological variability. Drought is a common feature in the country. During the 1984–5 drought, for example, GDP declined by 9.7 percent, agriculture output declined 21 percent, and gross domestic savings declined 58.6 percent (World Bank 2006). The unmitigated hydrological variability currently costs the economy more than one-third of its growth potential (World Bank 2006). Its current extremely low levels of hydraulic infrastructure and limited water resources management capacity undermine attempts to manage variability.

The inherent extreme meteorological and hydrological variability and the low level of water resources related socio-economic development in Ethiopia indicate the urgent need to enhance for better water resource planning and management practices that will stimulate and accelerate the agricultural based economy and improve quality of life of the citizens. Hence, given the rapidly growing population in the foreseeable future, these resources will have to be tapped and harvested in order to attain food security and improve the overall livelihood of the people. The population of Ethiopia was estimated as 73million in 2007 national census and the central statistical agency predict the population size will be 96million and 120million in the year 2015 and 2025 respectively.

The EFDR government has taken significant steps towards improving overall water resource management of the county by formulating the National Water Resources Management Policy, the National Water Sector Strategy, and the National Water Sector Development Programme (WSDP). The overall goal of the policy document issued in 1999 is to enhance and promote all national efforts towards the efficient and equitable utilization of the available water resources of the country so as to ensure significant socioeconomic development on a sustainable basis. The specific objectives of the policy are to: (i) promote the development of the water resources of the country for economic and social benefits of the people, on an equitable and sustainable basis;(ii) allocate and appropriately apportion the water, based on comprehensive and integrated plans, and optimize the allocation principles that incorporate efficiency of use, equity of access, and sustainability of resources; (iii) Manage and combat drought as well as other drought associated impacts, and disasters through efficient allocation, redistribution, transfer, storage and efficient use of water resources; and (iv) conserve, protect and enhance water resources and the overall aquatic environment on a sustainable basis. The National Water Sector Strategy (WSDP) was formulated in 2001. This aimed to provide a road map to translate the National Water Policy in terms of ways and means to attain the national water development objectives. In 2002, the government of Ethiopia translated the National Water Resource Management policy into action by formulating a fifteen years (for the period 2002 to 2016) National Water Sector Development Action Plan. During the plan period, the government envisages the development of 273,829 hectares additional irrigable land. The GoE has also recently promulgated a progressive proclamation (proclamation no. 534/2007) to set up basin management organizations to improve holistic water resources planning and management. The proclamation derives substantially from the Ethiopia Water Resources Management Policy and serves as a legal basis for the creation of individual or combined river basin organizations (RBOs) for all the river basins of Ethiopia - including High Basin Councils as decision making bodies with River Basin Authorities as their technical arm. A key task of the RBOs will be to formulate and monitor the implementation of sub-basin plans for integrated water resources management. To this end the Abay and Awash basin authorities have been established and star their operation.

Although Ethiopia has fairly good water resources and enabling working environment, these resources have neither been developed nor managed well, leaving populations vulnerable to the destructive impacts of water and climate variability, while not providing benefits from effectively harnessing the water and land resources. To mitigate against the economic impacts of water shocks in Ethiopia and to de-link economic performance from rainfall and enable sustained growth and development, the planning, development and management of water storage and distribution facilities both natural and manmade at all scales must be seen as an economy-wide development priority. In view of this, the EFDR government has given a due attention in developing and managing water resources systems of the country in its GTP that has a planning period of five years from 2011 to 2017. Accordingly in its five year GTP very ambitious water resource development plans are targeted. These comprises an increase of water supply coverage from 68.5% to 98%, an increase in hydropower generation from 2000MW to 10000MW and an increase in large and medium scale irrigation development from 127242.6ha to 785582.6ha (MOFED 2010). Despite the practicality of the plans and policy on the ground, the concern and focus given to the water sector by the government is an important initial step and may be taken as an indicator for the presence of clear understanding, willingness, commitment, and enabling environment at higher level in appropriately harnessing and using the most vital resources for the development of the national welfare. Ethiopia's great hurdle in realizing those plans and in the overall planning and management of its water resources are the limitation in finance and institutional capacities.

3.2. Location and general characteristics of the study area

3.2.1. Description of Abay basin (location, area, topography, climate, and hydrology)

The Abbay river or Blue Nile is located in the north western region of Ethiopia between 7^0 40´ N and 12^0 51´ N latitude, and 34^0 25´ E and 39^0 49´ E longitude. It originates from Gish spring found in Sekela woreda of west Gojam administrative zone of Amhara national regional State. From its source it flows to the north to feed Lake Tana. It flows south from Lake Tana and then west across Ethiopia and northwest into Sudan. From Lake Tana, the Abbay travels 35 km to the Tiss isat falls, where the river drops 50 m; it then flows through a gorge. The basin has an average annual run-off estimated to $50Bm^3$. Abbay is the most important river basin in Ethiopia. It accounts for 17.5 percent of Ethiopia's land area, for about 50 percent of its total average annual runoff which emanates from the Ethiopian highlands, for 25 percent of its population and for over 40 percent of its agricultural production. 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). A number of tributaries joined Abbay River in Ethiopia: Beshilo, Derame, Jema, Muger, Finchaa, Didessa and Dabus from the east and south; and the Suha, Chemoga, Keshem, Dera and Beles from the north. The basin has the lion's share on

Ethiopia's hydropower potential. Most of the suitable hydropower sites are in the middle and lower portion of the basins. Several large hydropower projects of regional (for east and horn of Africa region) significance are being planned in the middle and lower reaches of the Abbay River such as Karadobi, Mandaya, Beko Abo, and Boarder. Among these plans the construction of the boarder called renaissance dam is started in March, 2011.The flow of the Blue Nile reaches its maximum discharge in the main rainy season from July to September. It supplies more than two thirds of the water of the Nile River. The Blue Nile eventually joins the White Nile at Khartoum, Sudan and the Nile continuous through Egypt to the Mediterranean Sea at Alexandria. It is the main source of water for Ethiopia, Sudan and Egypt. Approximately 60% of Ethiopia's water resources flow into the Nile River system. The tributaries of the Nile running from the Ethiopian highlands contribute 86% of its water flow to Nile-river. Very brief description of the hydrology and water resources systems of Nile basin is given in appendix C.

3.2.2. Description of Tana sub basin (location, area, topography, climate, and hydrology)

Lake Tana, a natural reservoir, is the largest fresh water body in Ethiopia with a maximum depth of 14m and mean depth of 9m. It is located from 11.62^0N to 12.31^0N latitude and from 37.01^0E to 37.64^0E longitude with average natural altitude of 1786meter above sea level (m asl). At similar elevation the lake has a surface area of about 3050km^2 with length of 74km and 68km width and storage capacity of 29km^3. It is the head water of the Abbay (Blue) Nile River. The lake is shallow with weak seasonal stratification. There are four perennial rivers (Gilgil Abbay, Megech, Ribb, and Gumera) and many other seasonal streams in the sub basin that fed Lake Tana. Kebede et al. (2005) have indicated that 93% of the inflow to the Lake is from the four major perennial tributaries. Abbay River is the only natural outflow from the Lake. The authors have estimated the mean annual outflow from the Lake as about 3.5km^3. This is about 7% of the total flow of the Blue Nile, which contributes about 62% of the total flow of the Nile at the high Aswan dam (McCartney et al. 2008).

The Lake sub basin has an area of 15320 km^2 with an average elevation of 2025m asl (Studio Pietrangeli 1990). The geographical location of the sub basin extends from 10.95^0N to 12.78^0N latitude and from 36.89^0E to 38.25^0E longitude. The altitude in the basin ranges between 1788 and 3712 m asl. It is mainly flat around the lake within a range of 1750-1850 m asl. Annual Rainfall distribution ranges from 964 mm up to 2000 mm in the basin. Higher rainfall 1400 - 2000 mm is observed in south of the lake. Relatively lower rainfall, 1100 - 1400 mm is observed north of the basin (Awlachew et.al. 2007). The average annual rainfall in the sub-basin is about 1350mm and is concentrated from June-October. Although there is still uncertainty associated with the hydrology of Lake Tana sub basin, the Hydrologic study conducted by SMEC International Pvt. Ltd. indicates that the estimated annual inflow into the lake is about 4.9 Bm^3, annual rainfall over the lake about 3.8 Bm^3, evaporation from the Lake is about 5.07Bm^3, and the Lake outflow is about 3.7 Bm^3/yr (SMEC 2008b).

At the natural outlet of the Lake a weir is constructed and commissioned in 1996. Initially the weir had only two gates, each with a capacity of 70 m^3/s and operated to improve power production from the Tis Abbay-I power plant located at 35km downstream of the Lake. Five additional gates, also of capacity 70 m^3/s, were added to the weir in 2001, in association with the second power station (Tis Abbay-II, 72 MW) located in adjacent to Tis Abay-I power plant. The weir regulates water storage in Lake Tana over a 3 m range from 1,784 to 1,787 m asl. The active storage of the lake between these levels is about 9,100 Mm^3, which is approximately 2.3 times the average annual outflow. Regulation for power production has modified the natural lake level regime, resulting in reduced seasonal but greater inter-annual variability. The lowest water level ever recorded was in June 2003 when it dropped to 1,784.26 m asl. This was a drought year in much of Ethiopia and hydropower production was constrained in many places. To maintain electricity supplies production in the country the production at Tis Abbay power plant was maximized and as a result the lake levels declined sharply. The consequences were very significant to Lake transportation. Navigation had been ceased for approximately 3 months when the lake level dropped below 1,784.75 m, the minimum level on which boats and ferries can operate safely. But since 2010 another artificial outlet, that diverts an average flow of 77m^3/s to the adjacent Beles basin for the production of 460MW hydropower,   has been constructed at its western shore (SMEC 2008c).

3.3. Lake Tana sub basin water resources systems potentials and challenges

Lake Tana sub-basin has immense natural resources potential for growth. The sub-basin's water, land, livestock, forests, fishery, cultural, and other environmental assets offer considerable social and economic benefits to the livelihoods of the people lived in several towns and scattered rural settlements. Hence, the EFDR government in PASDEP had identified Tana and the adjacent Beles sub basins as the first of the five proposed growth corridors (zones) in the country (MoFED 2006). Huge investment plans have been prepared to develop the water resources of these sub-basins. In line with this the constructions of some water conveyance and storage structures for hydropower and irrigation development have been started in Lake Tana and Beles sub-basins. Tana-Beles integrated hydropower and irrigation development project, that has an installed capacity of 460MW of power production followed by 175,000 ha of irrigation and supplied by Lake Tana at an average supply rate of 77m^3/s (SMEC, 2008c), is the biggest among the planned projects in the sub-basins. The construction of the hydropower project is completed and commissioned in May, 2010. The construction of 175000ha of irrigation, which is used exclusively for sugar cane production and located in Beles sub basin, is on progress. The construction of a storage Dam for irrigation of 7000ha of land on Koga River, a tributary to Gilgel Abay, is also completed. The constructions of some other Dams, for example Ribb dam, in Tana sub-basin are still going on.

Though Lake Tana and its catchment are very valuable resources they are also ecologically fragile. Lake Tana is showing growing signs of stress resulting from several social, environmental, economic and institutional factors that need to be addressed in order to ensure sustainable development of its sub-basin in a manner that optimizes its socioeconomic benefits while protecting its valuable environmental and cultural resource base. The management of Lake Tana needs very careful planning and operation management that neither withdraw significant water from the Lake nor allow the storage of excessive floods. Both the excessive withdrawal and storage have their own effect on either reducing the Lake level and its surface area significantly or producing flooding problems in the flood plain area surrounding the lake. There are practical testimonies that justify these situations. Given Lake Tana and its immediate surroundings have a multipurpose function that has national and local significance, the following issues are of general importance in considering its development.

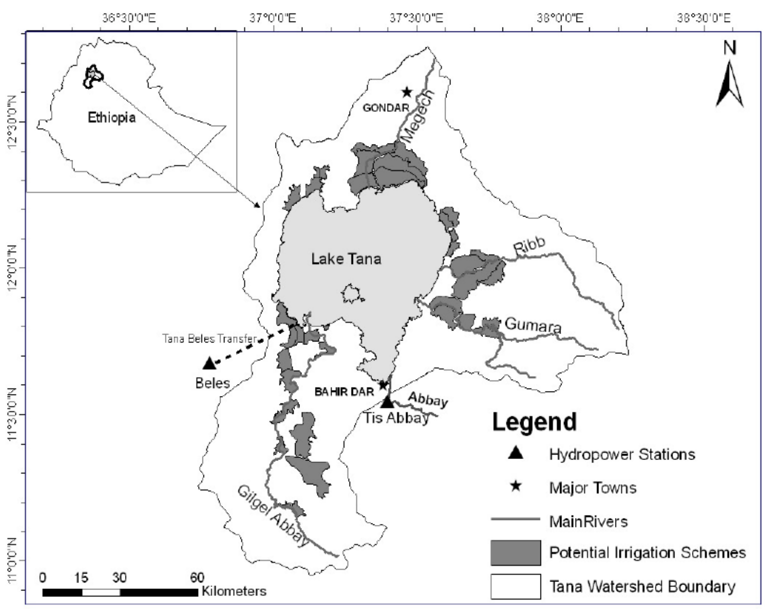


Figure 3.2 Lake Tana sub basin Water resources systems

3.3.1. Agriculture and Livestock

Lake Tana sub basin is one of the most densely populated areas with a population density of over 250 people per square kilometer of land area. An estimated 4.0 million people live in the sub basin (World Bank 2009). Agriculture is the basis for the livelihood of more than 80% of the population living in the sub basin. Agriculture production in the sub basin is dominated by small farmer production focusing largely on products for on-far consumption. Crop production and the rearing of livestock are closely integrated on the small farms, with livestock utilizing crop residue and providing draft power for ploughing and transport. The major crops grown on about half a million hectares of cultivated land (on 450,000 ha rain fed, and 6,000 ha floodplain irrigation, 500 ha small-scale irrigation, and 7,000 ha irrigated area at Koga) are cereals (77%), pulses (17%), oilseeds (6%), and vegetables, root crops and fruits (<1%). The sub-basin has nearly 5.9 million cattle for local use and trade. The agriculture production for most of the farmers in the sub basin is based on rain fed but those who live in the flood plain and the area around the Lake are also using the residual moisture after flood for some crop productions and those who live near the Koga reservoir are using irrigation. Live stock is also an important component of the farming system in sub basin contributing to an estimated 12.5% of the sub basin GDP (World Bank 2009).

3.3.2. Tourism, transportation and recreation

The Lake is home to several natural and cultural assets that are an important part of the Ethiopian identity and tourism. Proper operation and management of the Lake may maintain these important heritages of the Lake and its sub basin. Lake Tana sub basin contains Gondar Castles, island monasteries in Lake Tana as well as the Blue Nile Falls, as major tourist attractions. These natural and historical heritages have been proven to attract many international and local visitors to the sub-basin annually. The “Tis Esat” fall (water that smokes) is known to be one of the tourist attractions in the country. Moreover, the lake shore at Bahir Dar and Gorgora (a town in the northern shore of the Lake) are observed to be more suitable for recreation and would attract more local tourists and could be coupled with tourism to generate more income in the future. Besides, its proximity to other tourist attraction sites such as Semien Mountains, Axum steles and rock-hewn churches at Lalibela has capitalized the importance of the Lake and its catchment for tourism industry. Lake navigation is also an important mode of transporting people and goods to various towns and centers across and inside the lake. The peoples who are living in the islands are using both local made and modern boats as their means of transportation for making their day to day business. It is common though not desirable that most of these people are leading their life mainly by supplying fire woods to Bahir dar residents by transporting it across the Lake using their local made boats. Peoples living on towns on the shore of the Lake such as Bahir dar, Gorgora and Kunsila are also connecting easily through the boats and ferries transportation on the Lake. The transportation service rendered by the Lake is by far one of its most socio-economic benefits.

3.3.3. Hydropower development

In many cases, because of the huge temporal variability of stream flows, the development of hydropower project requires the construction of Dam and creation of Storage to maintain a regular supply of water to the power plant so as to generate the desired power. This requires huge investments which hinder most developing countries to utilize their resources timely in making a significant support to the development of the nations. However, Lake Tana, one of the best nature's gifts to Ethiopia, has unique natural characteristics that make it suitable for generating hydropower in the absence of artificial storage. Generation of hydropower in Lake Tana sub-basin has been started since 1994 by constructing Tis Abbay I hydropower plant that has an installed capacity of 11 MW. Later investigations on assessing the existence of other possibilities to further harness additional power in the sub basin reveal the availability of other suitable sites that can be coupled with the Lake to generate additional power. This led to the realization of Tis Abbay II and Tana Beles Hydropower plants that has an installed capacity of 73MW and 460MW respectively. Tana Beles hydropower and irrigation project involves inter-basin transfer of nearly 2.9Bm^3 of water per year from Lake Tana to Beles sub basin through an 8.1km head race and 12km tail race tunnels of 7.1m inner diameter each. The dual purpose of this inter-basin transfer is to use the large elevation difference, that provides a net head of 311m, between the lake and the underground powerhouse for the generation of hydropower, and to use the water downstream of the power plant for irrigating 175000ha of land which is the other additional natural benefit secured from Lake Tana.

3.3.4. Irrigation development practices and future plans

Ethiopia has 3.73million ha of irrigable land potential which comprises 3.3% of its total surface area and 6.7% of its arable land. The irrigable land in Abbay basin alone comprises approximately 22% of the total irrigation area in the country. Lake Tana sub basin is identified as one of the most suitable sub basin for irrigation development in Abbay basin. The sub basin has approximately100, 000 ha of irrigable land that accounts more than 8% of the land area (excluding the lake area) of the sub basin. Even though the sub basin has immense irrigation potential, so far there are no large scale irrigation projects implemented in the sub basin except Koga irrigation project. However, there are some small-scale irrigation schemes with a total area of a few hundred ha. Apart from these small schemes and some traditional irrigation, flood recession agriculture is common around the lake when flood waters recede and the lake level drops. Crops grown increasingly include maize and rice. Nowadays many potential sites as indicated in Table 3.2 for medium to large-scale irrigation have been identified in the sub basin. Thess six large multi-purpose dams (flood control, irrigation, etc.) are planned to be constructed on the major tributaries of Lake Tana that comprises Gilgil Abbay, Megech, Ribb, and Gumera. Together, the six dams will create a live storage volume of around 1.2B m^3, which is about one third of the mean annual natural outflow from Lake Tana (3.5B m^3).

Despite their indispensable socio-economic importance the decisions in realizing these very ambitious envisaged development plans in Lake Tana sub basin requires the consideration and analysis of various scenarios with appropriate planning and operational management tool to determine the most reliable and efficient alternatives that suites the social, economic and environment requirements. The authors have put their own efforts to show an alternative simple approach that can be used to evaluate the alternatives and made an assessment on effects of these development plans on Lake Tana characteristics and performance measuring indices.

Table 3.1 Size of Irrigable areas and their corresponding net water requirements in Tana sub basin

Name of project	Irrigable Area (ha)	Net Annual Water Requirement (Mm^3)
Megech Gravity	7,300	58.4
Megech Pump	24,510	196.1
Ribb	19,900	179.1
Gumara	13,980	113.2
Gilgel abbay	12,850	97.7
North east Tana	5,750	48.3
North west Tana	6,720	53.8
South west Tana	5,130	42.1
Total	**96,140**	**788.7**

The conceptualizations and methodology is described in chapter four and its applications are dealt in chapter six. The readers are kindly advised to go through these chapters for getting an insight on the approaches and applications of methodologies used in assessing viability of various development scenarios in comprehensive manner.

3.3.5. Fishery development practices and potential

The fishery potential in the sub basin arises from Lake Tana itself and the rivers that feed it. The majority of this potential is to be found in the Lake. Major concerns were raised on the exploitation and management of fisheries resources, notably large barb (Labeobarbus) stocks are highly vulnerable to increased fishing pressure, especially during aggregation of the ripe fish in the spawning season in the river mouths. Lake Tana is characterized by low nutrient concentrations and low water transparency due to high amount of silt in the inflowing rivers during the rainy season and the daily re-suspension of sediments in the inshore zone. Compared with Ethiopia's Rift Valley Lakes and other tropical African Lakes of similar depth, Lake Tana is not highly productive. The maximum sustainable fish yield of the Lake is estimated from 7-10 thousand tons per annum (World Bank 2009). The fishing industry in the sub basin is deemed to support the livelihoods of about 5000 people (World Bank 2009).

3.4. An overview of Lake Tana water quality characteristics

Management of water resources of a basin requires reliable information on water quality. This includes the collection, analysis and evaluation of water quality, and the assessment of the influence of human's activity on water quality. Water quality measurements become essential in order to enforce the laws developed on the basis of the above information as well as to evaluate the effectiveness of the management program. In Ethiopia, comprehensive and regular water quality monitoring and surveillance activities are lacking at all levels. Equally the attention given to Lake Tana water quality monitoring is also very less. In spite of the less concern and attentions given to the Lake water quality so far there is no known complaints and investigations showing some kings of quality deterioration. The physiographic characteristics of the Lake i.e. its shallow depth and inlet zone of the feeding rivers and the surrounding wetlands have their own contribution in maintaining its quality.

The shallow depth nature of Lake Tana, low temperature variation and presence of fairly strong wind after sunset generally allows the water to be well mixed. Hence there is no stratification layer in the lake. As a result of deforestation, degradation and high rainfall intensity very high suspended solids are observed on all rivers that fed the Lake. The sediment inflow to the lake is estimated to be 100million m^3/year (merid, 2005). This sediment inflow will increase if proper land management and soil conservation practices are not implemented. The effect of high suspended solid on the aquatic life is well documented. It absorbs heat from the sun, increase the water temperature and thus cause the O_2 level to fall down. The low dissolved O_2 level has negative effect on reproduction of aquatic organisms. Suspended solids can clog fish gills, reduce growth rates, and decrease resistance to diseases and decrease egg and larva development of the aquatic life. As it has been mentioned in section 3.2.2 the lake is feed primarily by four perennial rivers. The entrance locations of some of these rivers like Gigel Abay and Gummar are nearer to the outlet of the Lake that can facilitate short circuiting of sediment inflows i.e. it reduces the deposition rate of sediments.

In general the chemical constituent of Lake Tana is in line with the drinking water standards of Ethiopia which is shown in Table B15 in the appendix with respect to some known and measured chemical parameters. The Lake has low hardness, TDS and EC values. The pH of Lake Tana is slightly alkaline and within acceptable range of ambient standard for aquatic species as well as for drinking purposes. The existence of significant amounts of heavy metals like lead, mercury, and arsenic, e.t.c. in surface waters like Tana that do not receive both industrial and domestic wastes is very minimal and may be assumed the lake is still safe in these parameters. However, the rapid urbanization and the intensification in agriculture in the sub basin will change the constituents of the lake. The authors recommend the urgent need and implementation of standardized water quality monitoring and assessment program coupled with enforcement measures in the sub basin. Business as usual will not any more work and a failure in giving the required attention implementation measure pertaining to water quality will bring a severe consequences.

Table 3.2 Lake Tana water quality (source: Merid, 2005)

No	**Parameter**	**Value**
1	pH	8.43
2	TDS(mg/l)	162
3	EC(μS/cm)	194
4	Transparency (m)	0.31 to 1.82
5	Temperature ($^{\circ}$C)	22.3
6	Chlorophyll “a” (g/m^3)	3.1
7	Dissolved oxygen (mg/l)	6.5
8	Ca^{++}(mg/l)	18
9	Mg^{++}(mg/l)	9.7
10	Cl^-(mg/l)	8
11	Sio_2(mg/l)	22
12	$CO_3 + HCO_3$ (mg/l)	1.7
13	Hardness (mg/l)	84.9

4. Conceptualization and Methodology

4.1. Conceptualization

Modeling usually involves attempting four stages of model development processes that comprise conceptualization, formulation, calibration, and verification. Conceptualization involves consideration of all of the thought processes that take place and determining which specific processes are highly important in solving the problem at hand and devising an efficient and effective solution. Conceptualization requires understanding the problem and the processes that govern the situation and it accounts for as much as 80% of the effort in developing models (McCuen 2003). In view of the limitation in getting the required data and resources and having a clear objective in mind we have made an attempt to make a clear conceptualization and develop a model which can be applied in a simple straight forward manner so that it can be easily understood, manipulated, applied and interpreted.

In Lake Tana sub basin the availability of hydro-meteorological data is very scanty. In view of the ongoing and planned water resources developments in the sub basin it is crucial to have a reliable and up-to-date hydro-meteorological database. Without reliable hydrological data wrong decisions may be taken to develop the sub basin's water resource in an efficient and sustainable manner. Only the records for the Lake level and Lake Outflow measured at Bahir Dar are relatively reliable and adequate for any hydrological and water resources related planning and design works. Other gauging stations for runoff measurement are located at the upstream locations of the major tributaries of the lake. The total catchment area covered by runoff measuring gauge stations comprises only 40% of the entire size of the sub basin. SMEC (2008a) has discussed the adequacy and reliability of hydro-meteorological data in the sub basin and pointed out the major problems associated with the collection and acquisition of this data as:

- Many stations suffer from sedimentation, bank scouring, and in a few cases from bank overflow during high river stages.
- In most station there are no water level recorders and the hydrometric team do not have current meter that can be used at high river stages.

This indicates not only the inadequacy of the hydrometric stations spatial coverage but also the problems in getting reliable data from the existing stations. Besides, the Lake covers a large surface area at an average depth of 9.0m. In such situations water from the Lake may either percolate towards the surrounding aquifer or groundwater from the aquifers may enter to the lake or there may not be interaction at all. So far there is no clear scientific explanation that pointed out the existence of either of these situations. Even the attempts made in getting to know the situations are very limited. One of the hurdles in this regard is the Lack of adequate and appropriate measured data. Indeed investigation of groundwater requires the collection of data through provision of conceptually designed and installed monitoring station in the vicinity of the study area. So far there are no such monitoring stations in the vicinity of Lake Tana and hence the phenomenon is still a mysterious. Most previous studies involved in planning and management of Lake Tana's water resources systems made a simple assumption that there is no interaction between the Lake and the surrounding aquifers. Introducing such a crude assumption without any sort of physical and/or scientific evidences is made to simplify the complex situation at the expense of huge uncertainty.

There are nearly 34 meteorological stations in and around Lake Tana sub basin. However, SMEC (2008a) has also assessed the problems in the meteorological stations and it indicated that there is unevenness in spatial distributions and there are many missed data in some of the station. For example there is no rain gauge station in the lower part of Gilgle Abay, one of the biggest tributaries of Lake Tana that covers nearly $1000km^2$. This indicates the available meteorological stations are not sufficient to adequately represent the sub basin in providing the required climate information.

There are neither measuring devices nor other regionally tested and acceptable techniques in quantifying the runoff generated in the downstream catchments from the gauging stations. The absence of measured data and/or other regionally tested and approved techniques for runoff quantification makes water resources systems planning and management task in Lake Tana sub basin more complex. However, this need not delay or restrict our attempt to find other alternative methods that will help us towards the creation of more sustainable water resource systems planning and management scenarios in the sub basin.

The absences of sufficient and reliable records of inflows in the sub basin have hindered the effective use of conventional approaches to evaluate and reevaluate the characteristics of Lake Tana. Quantifying performance measuring indices like reliability and resilience of Lake Tana and reassessing them in light of various development scenarios and information is one of the classical problems that have not been solved yet. Despite the limitations in getting adequate and reliable hydro-meteorological data in Lake Tana sub basin, one has to look either for methods to estimate the inflows from the ungauged catchments or device another conceptualization. Estimating the runoff generated from the ungauged catchment may be associated with high uncertainty because of the heterogeneity of the catchments in the upstream and downstream of the gauging station and the inaccuracy and inadequacy of the available data in the gauging stations. In such situation devising other mechanisms that use only reliable records i.e. Lake Level and Lake Outflow in quantifying the performance measuring indices (sustainability criteria) is very indispensable. In order to assess the reliabilities and resiliencies of Lake Tana based on only the Lake level and outflow data may require an in depth understanding and subsequent formulation of the problem.

It is obvious that these indices can be easily estimated by examining the behavior of the Lake or its response to various input output interactions. For this purpose knowing all the water balance terms of the Lake may be required which are very uncertain because of lack of adequate and reliable data records. Conceptualizing the problem in view of the available data leads to the formulation of two approaches name as direct and indirect approach. The direct approach is the use of net inflow series and the indirect approach is the use of the Outflow series only based on the application of equivalent catchment concept.

4.1.1. Net inflow approach

This approach considers the actual conditions and all the water balance terms of the Lake. It tries to see the problem from the supply side and with due consideration of all the elements an estimate for the net inflow or supply is obtained. As it is indicated above, among the water balance terms of Lake Tana, only the Lake Level and Lake Outflow have relatively sufficient and reliable records. Using these terms and the water balance equation the volume of the net inflow (P_s) can be obtained as:

$$(Q_{in})_t + P_t - E_t \pm (Q_g)_t - (Q_{out})_t = \Delta S = S_t - S_{(t-1)}$$

$$(Q_{in})_t + P_t - E_t \pm (Q_g)_t = S_t - S_{(t-1)} + (Q_{out})_t$$

$$(\text{Net Inflow})_t = (Q_{in})_t + P_t - E_t \pm (Q_g)_t$$

$$(\text{Net Inflow})_t = S_t - S_{(t-1)} + (Q_{out})_t$$

$$\text{Let } P_s = S_t - S_{(t-1)} + (Q_{out})_t$$

$$P_s = S_t - S_{t-1} + (Q_{out})_t \qquad (4.1)$$

Where for any time period t, Q_{in} is the inflow to the Lake, P is the direct precipitation, E is the evaporation, Q_g is either ground water inflow to the Lake or recharge of the surrounding aquifer by the Lake, Q_{out} is the outflow from the Lake through the natural out flowing river, s is the storage ΔS is the change in Lake storage in successive time periods, and P_s is the net inflow of the water balance terms. All terms in the water balance equation are in volumetric unit. Conceptually the net inflow computed from the backward calculation of the water balance equation of the Lake is more reliable, provided that accurate measurements are taken for Lake Level and Outflow data, as it considers all inflows and outflows. The water balance elements are shown in the Figure 4.1.

The concept of stochastic hydrology can be applied on the net inflow and evaluation of reservoir characteristics such as yield, and reliabilities can be obtained. This approach can eliminate the approximation made for most uncertain water balance terms like the Lake inflow and it is comprehensive as it includes all possible inputs and outputs. Furthermore, it is easy to account the serial correlation and seasonality of the uncertain and unmeasured water balance terms of the reservoir in the net inflow series.

Conceptually it is clear and simple to understand and computationally it is efficient. Here the availability of insufficient hydro-meteorological data in the entire Lake Tana sub basin may be taken as an excuse for not to employee other conventional modeling approaches in modeling the reservoir systems.

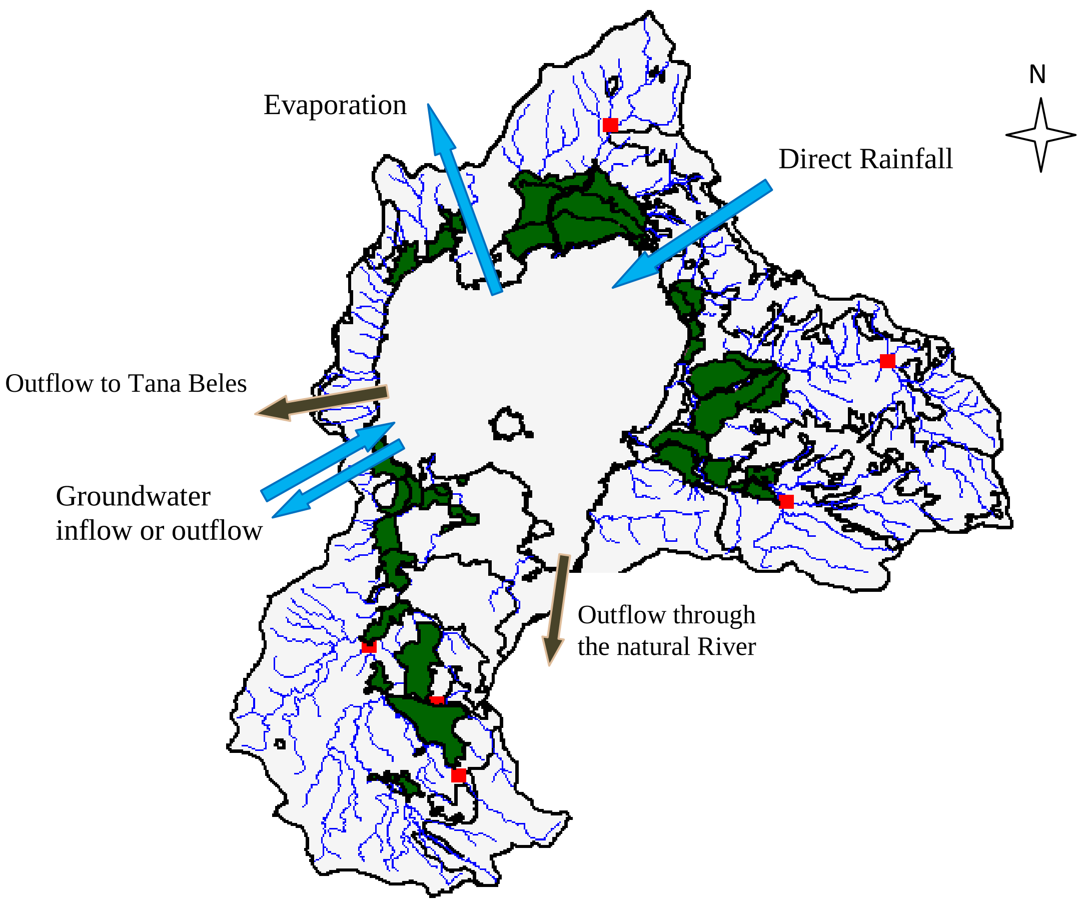


Figure 4.1 Lake Tana's Inflow and Outflow representation

4.1.2. The net supply approach

In the context of Lake Tana sub basin, the word "net supply" is used to represent the outflow measured at the outlet of the sub basin. It denotes only the surface water part of the sub basin yields. It is obvious that the net supply capacity of a catchment is the most vital available and usable resource for various socio economic activities and environmental regulation. The effectiveness and efficiency of any water resources planning and management attempt is highly dependent on the accuracy and reliability of the methods used in estimating the net supply capacity of a catchment. In most cases direct records of net supply of a catchment is not obtained prior to the development of water resources systems like reservoirs. The common procedure is estimating all the inputs and anticipated loss in the reservoir and makes a mass balance analysis to estimate the net supply. Though it is a common practice it has limitations especially in areas where there is a limitation in getting adequate data for the desired analysis. The results of the analysis are usually affected by uncertainties resulted from the natural variability of the variables and the models used for estimating them. But in Lake Tana sub basin because of the existence of the natural Lake, which is used as a storage for balancing the supply and the demands, all the system inputs and loss have been naturally accounted and the Outflow measured just at the outlet of the Lake is the net supply. The availability of this record is a great opportunity to make very simplified analyses and designs associated with the proper planning and management of the sub basin water resources. In using the net supply we need not worry about the amount of inflows to the reservoir, evaporation, direct precipitation, and groundwater interactions. All these input and outputs have been naturally accounted and the record at the Outlet represents the Lake's responses to such various input output interactions. Here the implicitly assumption based on the existing practice is that regulating the Lake Outflow for the purpose of balancing demand and supply and using it as a reservoir will not have a significant change in the natural characteristics of the Lake. The Lake has relatively large surface area and hence a small change in depth measured from its surface is sufficiently enough to balance the mismatch in supply and demand. A very small increase or decrease in depth will have a significant change in its active volume without making a significant change in its surface area. In its natural as well as regulated conditions the decrease or increase in its surface area from the average is not more than 2.5% of the average surface area. Characteristics of Lake Tana are shown in appendix B Table 16. Regulating the Lake outflow will affect only the temporal variations of the Lake characteristics which are deemed to be very minimal in bringing a significant change in the overall hydrological processes of the Lake.

In its natural condition, i.e. in view of maintaining the natural integrity of the sub basin, the quantity of surface water that can be extracted from the sub basin for various socio-economic activities is limited to only the net supply amount. It is not possible to extract more surface water, unless the losses are reduced by some mechanisms, than the net supply amount. Loss reduction such as evaporation from the Lake is practically impossible without significant reduction in its surface area. If an amount more than the net supply is withdrawn from the sub basin it will be mining of the sub basin particularly the Lake. Hence the system output or supply capacity is limited to its net supply. All water resources planning and management efforts in the sub basin should therefore acknowledge the limitation in the potential of the quantity of surface water and make a clear conceptualizations and methodologies for its proper development and allocation. Here the author would like to advocate how a methodology designed based on entirely the net supply is used in planning and managing the sub basin water resources. Like the net inflow the net supply series can also be used for evaluating the performance measuring indices of Lake Tana.

For simplicity and clarity of the application and viability of the approach it is desirable to simply represent the whole sub basin including the Lake by an equivalent hypothetical catchment i.e by an equivalent system. Such representation by equivalent hypothetical catchment will simplify the situation and enable any one to solve storage related problems easily. For example let's assume that the hypothetical catchment shown on the right side in Figure 4.2 is an equivalent catchment to Lake Tana sub basin. The concept of equivalency here denotes that for equal inputs such as rainfall to both catchments there will be equal Output from both catchments.

It may be paramount important to apply here the concept of system approach to understand further the application of the net supply approach. We may consider the sub basin or its equivalent catchment as a system with inputs and outputs and some system interacting elements and processes like evaporation, evapotranspiration, infiltration, runoff, overland flow, and interflow e.t.c. As a system it has inputs and outputs and interacting and interrelated elements. The system output is its net supply capacity. From water resources systems analysis perspective it is possible to entirely depend on the system output i.e. the net supply by simply treating the system as a black box with no detail information and knowledge on system elements and their interaction. In the context of Lake Tana, even if quantifying all the system elements is desirable, the most important thing relays on the appropriate utilization of the system output. Such simplification and conceptualization helps to avoid the uncertainties associated with the estimations of the Lake water balance terms and leads us to focus only on devising mechanisms on how to use the system output in an efficient and sustainable manner.

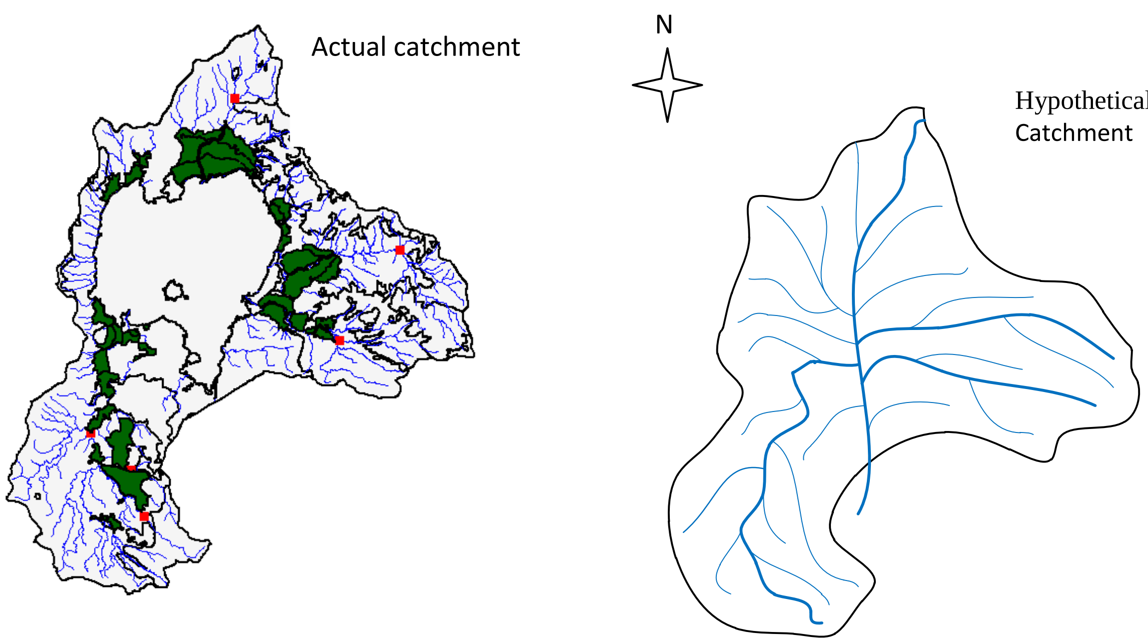


Figure 4.2 Lake Tana actual and its hypothetical equivalent catchments

In general the equivalent hypothetical catchment concept has the following significance:

1. It helps to see the propblem from a simple watershed prespectives and significantly reduces the complexity
2. It elliminates the problems associated with date limitations.
3. It reduces the uncertainties arising for the use of several input-output variables
4. It also helps to apply reservoir design and operation techniques very easily.

The conceptualization can easily and conveniently be applied from the very beginning of assessing the need for storage and its design to reevaluating its performance in various development and operation scenarios. So, before running to assess Lake Tana's performance it is important to determine first the volume of storage required to balance the supply and demand difference at the outlet of the sub basin. In such conceptualization the outflow or net supply series of Lake Tana sub basin can be taken as the outflow series from its equivalent ideal catchment. It is easy now to perform any storage related analysis or design for the equivalent catchment. The available storage design and analysis techniques can easily, conveniently and confidently be applied to the ideal catchment. After determining the required storage capacity to balance the differences in supply and demand an attempt is needed to reverse it to the existing condition. This will help to clearly understand the problem and able to solve it easily. Though we call it as indirect approach it is very straight forward and simply. As compared to the net inflow approach the uncertainties associated with it are very less as it only use the outflow data.

Lake Tana has a surface area to active volume ratio of approximately 333. This high surface area to active volume ratio has to be considered when choosing a methodology for performing some kinds of storage related analysis. A very small decrease or increase in Lake Tana's level has a significant change in its active volume. For example a change in one centimeter in its Lake Level is approximately equivalent to 30 million cubic meter of water which is nearly equal to the Outflow from the Lake for the month of May. This indicates that a very small difference in Lake Level amounts has a significant impact on result obtained from it. Besides, because of high surface area of the Lake the effect of its water balance terms like direct precipitation and evaporation need to be considered carefully in planning and managing the sub basin's water resources and have to be determined using an appropriate methods that can give reliable estimates. The net supply approach is therefore preferable as compared to the net inflow approach because it uses only the Outflow data. In both approaches stochastic analysis can be used for generating different realizations. The conceptualizations and their subsequent modeling processes can actually lead to a better understanding which eventually can result in improved decisions being made in the planning and management of the sub basin's water resources systems.

4.2. Methodology

4.2.1. Description of Stochastic analysis and its applications

The planning and management of water resources systems involves the collection and analysis of many hydro-meteorological data which are known with the property of possessing an inherent natural variability. For example, stream flow, precipitation, evaporation, water demand, and other hydrological and meteorological variables are highly stochastic in nature and are good examples of time series data that are most often used in the planning and management of water resources systems. Time series is defined as a sequence of values arranged in their order of occurrence in time (Box et al. 1994). Measured historical data are limited in extent and accuracy. The future is always uncertain. Consequently, reservoir related studies necessarily involve uncertainties and approximations. Considering the stochastic nature of these data is very vital while using them for various purposes i.e. the stochastic nature of these data must be reflected in methods used to quantifying the magnitude of some decision variables associated with these data. In view of this the application and use of stochastic modeling in water resources systems planning and management is very indispensable.

Using stochastic modeling, sequences of any specified length for a variable such as monthly stream flow can be synthesized. The synthetically generated data will then be used to simulate the physical process under consideration. This will gives opportunities to consider various possibilities and domains of the process and problems under investigation and will avoid the entire dependency on historical data alone. Working with historical data alone has a problem that the future may not be an exact replica of the past. In using historical data alone there is always unknown level of risk assumption. However, stochastic modeling will help us to estimate the risk associated with the preferred design. In addition to this stochastic modeling can also be used to make a reasonable forecast.

In time series analysis, the order of occurrence of the observations is crucial. If the chronological ordering of the data were ignored much of the information contained in the time series would be lost. A set of quantitative observations such as stream flow measured in discrete time interval and arranged in chronological order is an ideal example of time series. The time series to be analyzed may then be thought of as a particular realization, produced by the underlying probability mechanism. The Outflow series recorded from Lake Tana sub basin out let and the net inflow series of Lake Tana obtained from equation 4.1 are single realizations among other perhaps many different possible realizations in their respective stochastic processes. Since 1960s examining the time dependency of such series and generating other possible realizations is identified as one of the most appropriate applied techniques to the planning and management of water resources systems.

A statistical phenomenon that evolves in time according to probabilistic laws is called a stochastic process (Box et al. 1994). One of the important classes of stochastic processes is the stationary processes. Stationarity of a stochastic process can be qualitatively interpreted as forms of statistical equilibrium, and in particular, vary about a fixed mean. In order to simplify the mathematical theory underlying a stochastic process, it is often assumed that the stochastic process is stationary. Therefore, the statistical properties of the process are not a function of time. For example, except for the inherent stochastic fluctuations, stationary stochastic models are usually designed such that the mean level and variance are independent of time.

There are many natural and physical processes, for example Lake Tana's net inflow, that exhibit the stationarity phenomenon. But all natural time series data may not possess stationarity property. Some time series data may have trend, jump, and seasonality components that can be detected by the time sequence plot of the series and the data set may be nonstationary. There are also common procedures in modeling nonstationary time series. The most commonly used procedure is to first remove the nonstationarity by invoking a suitable transformation and then to fit a stationary stochastic model to the transformed sequence. One method to remove nonstationarity is to difference the give data before determining an appropriate stationary model.

The principal assumption in using statistical models for a time series data is that the variable being analyzed is considered to be generated from an absolutely random process. Therefore, if the series contains unnatural components, such as some kinds of artificial regulations and manipulations for example regulated release from reservoirs, they should be examined first. Besides, the examination should also consider the existence of other deterministic components such as trend, jump, and seasonality in the time series data. To maintain the principal assumption in modeling time series data the first steps that should be taken is naturalizing the data and removing trend, jump, and periodicity from the data. The modeling of time series data usually assumes that the stochastic component, after naturalizing and removing the periodic components and time-dependence structure , is an independent and normally distributed series (Salas et al., 1988). The graphical test is the most commonly used test for testing the hypothesis that a given time series is normal. The other useful devices for describing the behavior of stationary processes are the autocorrelation, partial autocorrelation functions and the spectrum.

An intrinsic nature of a time series is that, typically, adjacent observations are dependent. The nature of this dependence among observations of a time series is of considerable practical interest. Time series analysis or stochastic analysis is concerned with techniques for the analysis of this dependence. The procedure of fitting a time series or stochastic model to the time series for use in applications is called time series analysis (Hipel and McLeod 1994). In time series analysis, one wishes to determine the most appropriate stochastic model to fit to a given data set. The fitted model can then be used for various important areas of applications such as simulation and forecasting. No matter what type of stochastic model is to be fitted to a given data set, it is recommended to follow the identification, estimation, and diagnostic check stages of model construction (Box et al. 1994).

Very brief descriptions of model construction stages are give here while their practical application is illustrated in chapter six. Salas et al. (1988); Box et al. (1994); and Hipel et al. (1994) have detail explanation on time series analysis. At the identification stage, the more appropriate models to fit to the data can be tentatively selected by examining various types of graphs (correlograms) resulted from the plot of the Autocorrelation function (ACF) and Partial Autocorrelation Functions (PACF). Box et al. (1994) have mentioned the sufficiency of using the autocorrelation and partial autocorrelation functions as tools to identify models most commonly applied in natural processes. The exact mathematical models of hydrologic time series are never known. The inferred population models are only approximations. The exact model parameters are also never known in hydrology since they must be estimated from limited data.

Because there may be a range of different families of stochastic models which can be fitted to the time series under consideration, one must choose first the group of models which are most suitable. The selections can be based upon a sound physical understanding of the problem, output from the identification stage, and exploratory data analyses. At the estimation stage, method of moment or maximum likelihood can be applied to obtain estimates of the model parameters. Subsequently the fitted model can be subjected to diagnostic checks to ensure that the key modeling assumptions are satisfied. In time series modeling the key modeling assumptions is that the model residuals are uncorrelated, normally distributed and have a constant variance.

When considering linear stochastic models such as the AR (autoregressive) or ARMA (autoregressive-moving average) one should check that the model residuals are not correlated, possess constant variance (i.e., homoscedasticity) and are approximately normally distributed. If the residuals are not white noise, the model should be redesigned by repeating the three phases of model construction. In practice, it has been found that a suitable Box-Cox power transformation can rectify anomalies such as heteroscedasticity and non-normality. The logic sequence underlying the traditional approach to stochastic model construction and application is displayed as a flowchart in Figure 4.3.

The basic statistical representation of the time-dependence structure is the correlogram, which shows the fluctuations of the autocorrelation coefficient of the series for different lags. The autocorrelation coefficient is a dimensionless measure of linear dependence that can be estimated as follows:

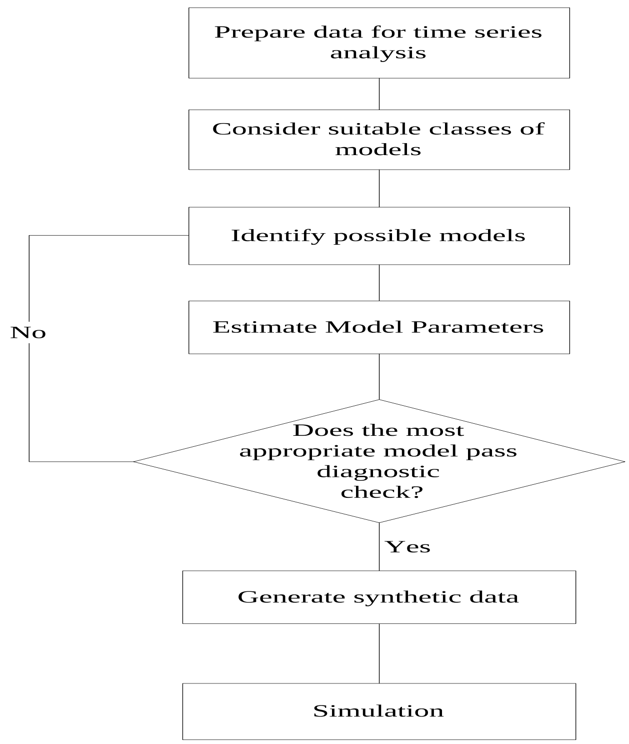


Figure 4.3 Time series modeling and application flow chart

$$r_k = \frac{\sum_{t=1}^{N-k}(x_t - \bar{x})(x_{t+k} - \bar{x})}{\sum_{t=1}^{N}(x_t - \bar{x})^2} \quad (4.2)$$

Where r_k is the lag-k autocorrelation coefficient and $\bar{x}$ is the sample mean. For an independent series, the population correlogram is equal to zero for $k \neq 0$. Even though correlograms of samples of independent series show fluctuations around zero, they are not necessarily equal to zero due to sampling variability. The 95% and 99% probability levels limits for the correlogram of independent series can be estimated using the following equations.

$$r_k(95\%) = \frac{-1 \pm 1.645\sqrt{N-k-1}}{N-k} \quad (4.3a)$$

$$r_k(99\%) = \frac{-1 \pm 2.326\sqrt{N-k-1}}{N-k} \quad (4.3b)$$

Where N is the sample size. Based on this test, autocorrelations falling outside of the probability limit indicate significant time dependence; otherwise, the series can be considered as an independent series.

4.2.2. An overview of common stochastic models to water resource planning and management

There are wide array of stochastic models. However, the authors have only considered and give very brief descriptions of those families of stochastic models that are commonly used in modeling water resources systems. In this regard those linear stochastic models applied for stationary stochastic processes in modeling water resources systems are the autoregressive, moving average, and mixed autoregressive moving average processes. The properties of these processes, in particular their correlation structures are described very briefly in the subsequent sections. The stochastic models are based on the idea that a time series in which successive values are highly dependent can frequently be regarded as generated from a series of independent "shocks" a_t. These shocks are random drawings from a fixed distribution, usually assumed normal and having a mean of zero and variance σ_a. Such a sequence of random variables a_t, a_{t-1}, a_{t-2} … is called a white noise process. The white noise process a_t is supposed transformed to the process Z_t by what is called a linear filter, as shown in Figure 4.3 adopted from Box et al. (1994). The linear filtering operation simply takes a weighted sum of previous random shocks a_t, so that

$$\begin{aligned} Z_t &= \mu_t + a_t + \psi_1 a_{t-1} + \psi_2 a_{t-1} + \cdots \\ &= \mu_t + \psi(\beta) a_t \end{aligned} \quad (4.4)$$

Where t is discrete time that occurs at equispaced time intervals, μ_t, is the deterministic component, a_t, is white noise (also called disturbance, random shock or innovation) at time t, and ψ_i is the i^{th} moving average parameter. The white noise a_t has the properties

$$E(a_t) = 0 \quad (4.5a)$$

$$Var(a_t) = \sigma_a \quad (4.5b)$$

The terms other than μ_t, on the right hand side of equation (4.2) form what is called an infinite Moving Average (MA) process. In general the deterministic component μ_t is a parameter that determines the level of the process which can be a function of time or may be a constant such as the mean level μ of a process and is the linear operator that transfers a_t into Z_t and is called the transfer function of the filter.

$$\psi(\beta) = 1 + \psi_1 \beta + \psi_2 \beta^2 + \ldots \quad (4.6)$$

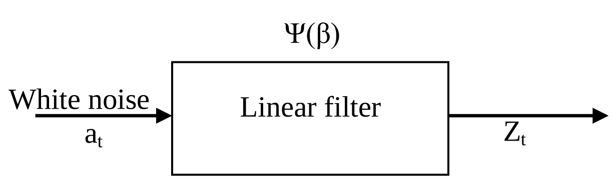


Figure 4.4 Representation of a time series as the output from a linear filter

4.2.3. Description of the application of stochastic analysis in Lake Tana's sub basin water resource systems planning and management

A time series is considered as one realization of the underlying stochastic process. However, it is obvious that there is not just one realization of such a process. In principle there are an arbitrary number of realizations which all have the same statistical properties as they all result from the same stochastic process. One of the major uses of time-series modeling is generation of synthetic values for many other realizations. The generation of synthetic time series often consists of the generation of independent variables in a series defined as a random process. The generated random component of a series will be added to its trend or deterministic component to reproduce the original time series. Usually in reservoir design and analysis synthetic inflows are generated and used to determine the characteristics of the reservoir.

In Lake Tana, both the observed Outflow and the computed net inflow series are single realizations that have been generated from their respective stochastic processes. These realizations are outputs from natural processes that can be modeled. The usual stochastic model development, calibration, and diagnostic check procedures have been adopted to identify suitable models that can adequately represent the outflow and net inflow series from Lake Tana catchment. After fitting the appropriate stochastic models to these series the fitted models will then be used to generate various statistically similar realizations. The synthetic generated realizations will then be used to assess the characteristics and performance measuring indices of Lake Tana in various development and management scenarios. Simulation using the synthetic generated data can also be used to determine operation rules and also to analyses the effect of upstream irrigation development and reservoir construction. Detail description of the application is presented in chapter six and seven. The applications will help us to clearly understand the situations in Lake Tana sub basin.

5. Data and Quality Check

5.1. Introduction

Availability of reliable and consistent hydro-meteorological data is one of the basic requirements for water managers to make well-informed decisions, and for researchers to make proper analysis and arrive at reasonably accurate conclusions. There are organizations in almost all nations that are responsible for collecting and recording the data in different formats and qualities and made available for use by other organizations or personnel with some rules and regulations. The data recorded in different formats and qualities have to be first examined and treated in such a way that there will be viability in using them. Data manipulation is therefore the processes that involve some preliminary graphical and statistical analysis used to confirm the viability of the data to the intended purpose. The preparation phase of data analysis involves compilation, preliminary analysis, and hypothesis formulation. The primary interest in the preliminary data analysis is to know whether a change in the criterion variable has occurred. Graphical analyses are often used as a first step in the preliminary data analysis. Graphing is an important modeling tool, but it cannot be used alone. Numerical and statistical indicators must supplement the information extracted from graphical analyses. Graphical analyses can provide some insight into the characteristics of the data sets and changes associated with it. In view of this, time series plots, box plots, probability plot, and some other graphical and statistical analysis have been used to assess the characteristics of the data sets used in this research. The hypothesis and speculation extracted from the graphical analysis and other observations have been further investigated using other quantitative methods. Applications of these methods are described in the following sections.

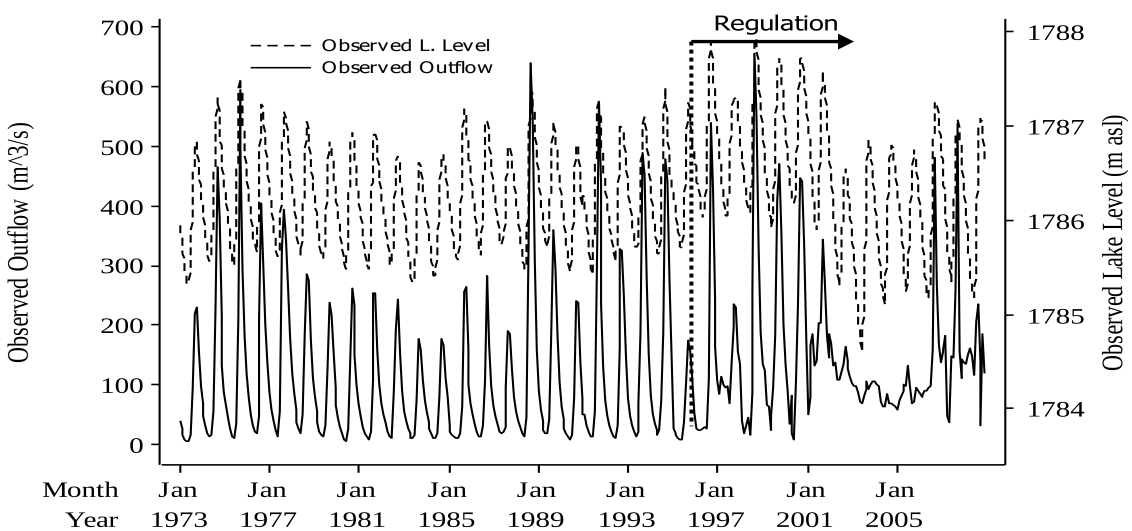
5.2. Missed data infilling

The Lake Outflow and Lake Level data are the most important data sets for the intended time series modeling and simulation processes. As indicated in chapter four there is relatively sufficient length of records for these variables since 1959. However, only the records from 1973 onward have been selected for further analysis. The records from1959 to 1972 have many missed data as compared to the records in other years and hence discarded from further considerations. The missed data in the selected records of the Lake Outflow and Lake Level have been filled by moving average techniques. The authors have recognized the limitation associated with the selected technique in which it might have an effect of averaging the randomness nature of the data. Since there are very few data missed its effect will not be significant in altering the overall characteristics of the data sets. The Outflow records for the year 1993 and 1994 were identical. This might happen by repeating the 1993 records for the 1994 or vice versa during data recording and encoding time. Otherwise there is very little chance of getting exactly identical flows in the natural system. This is one of the big data recording or encoding errors noticed in the data set. The authors have assumed that it is a simple repetition of either of the data onto another and corrected by replacing the original flow records of the year 1994 by the average of the previous years. After infilling the missed data for both Lake Level and Lake Outflow, time series plots for the complete data set are developed as shown in Figure 5.1 below.

5.3. Naturalizing the observed Lake Level and Outflow records

The principal assumption in using statistical models for hydrologic time series is that the variable is considered to be absolutely random and generated from a natural process. In deriving and applying reservoir storage yield relationships, it is desirable to use unregulated natural flows in order to apply correlation procedures (Augustine J.F 1975). Development of a complete homogeneous set of streamflow data represents a large portion of the total effort of yield study (Wurbs R. A. 1990). Gauged monthly streamflows must be naturalized to remove non-homogeneities caused by the activities of human beings in the basin. For example if the series contains unnatural components, such as regulated release from reservoirs or trends, they should be removed first. For the case of Lake Tana, as it is mentioned in chapter four, a weir has been constructed and commissioned in the year 1996 at the Outlet of the lake for the purpose of supplying a regulated flow to Tis Abay I and II hydropower stations which are found at 35km downstream of the weir. The Lake Level and Lake Outflow from year 1996 onwards are affected by the regulation rules of the weir gates and do not show the natural characteristics. The effect of this regulation in the Lake Level and Lake Outflow is clearly shown in the time series plots shown in Figure 5.1.

Figure 5.1 Time Series Plot of Observed Lake Level and Outflow



The regulation effects on both the Lake Level and Lake Outflow have to be first removed before using the data set to assess the characteristics of the Lake. To remove the regulation effect first it is important to know whether the active storage has over year or with-in year storage characteristics. Because in a with-in year reservoir balancing the supply and demand is limited to only a single water year. Here the balancing affects only the monthly distribution in a year. And there is no difference in the annual volume of the naturalized and regulated outflows. But in over-year storage the balancing goes beyond a single year usually it considers several years of supplies and demands and hence it affects both the yearly and monthly distributions. The regulated annual outflow from a with-in year reservoir can be simple naturalized by disaggregating it into monthly outflows.

As it is pointed out in chapter two there is no unique division between these two classes of reservoir behavior. However, a with-in-year storage reservoir is generally known with the characteristics of filling every year whereas over-year systems contain long multiyear drawdown periods and are seldom full. In its natural characteristics, Lake Tana is overflowing in all times every year but the regulation has changed the range of the reservoir and it might have changed its storage characteristics too. In its new range the reservoir may be changed to an over-year storage type. This situation can be assessed by using an index m, a useful index for classifying the behavior of water supply systems, introduced by Hazen (1914) and defined as:

$$m = \frac{(1-\alpha)\mu}{\sigma} = \frac{(1-\alpha)}{C_V} = \frac{(\mu - Y)}{\sigma} \qquad (5.1)$$

Where α is the annual yield as a fraction of the mean annual inflow μ, Y = average annual yield; μ and σ = mean and standard deviation of the annual inflows, respectively; and C_v = coefficient of variation of the annual inflows ($C_v = \sigma/\mu$). Vogel and Bolognese (1995) provided a history of the use of the index m in water supply applications. Greater values of m correspond to systems that tend to accumulate water in storage over time more than for systems with lower values of m. In this research we used m to differentiate Lake Tana's storage behavior and be able to determine whether it tends to refill at the end of each year (within-year) or whether it is seldom full at the end of a year (over-year) i.e. whether it exhibit within-year (seasonal) or over-year (carryover) storage behavior. Vogel & Stedinger (1987) suggest that as long as $0 < m < 1$, the system is dominated by over-year behavior, whereas if $m > 1$, the system is dominated by within-year behavior. They hypothesized that $m = 1$ can be considered as a demarcation between over-year and within-year systems because carryover storage requirements increase significantly as m decreases below unity.

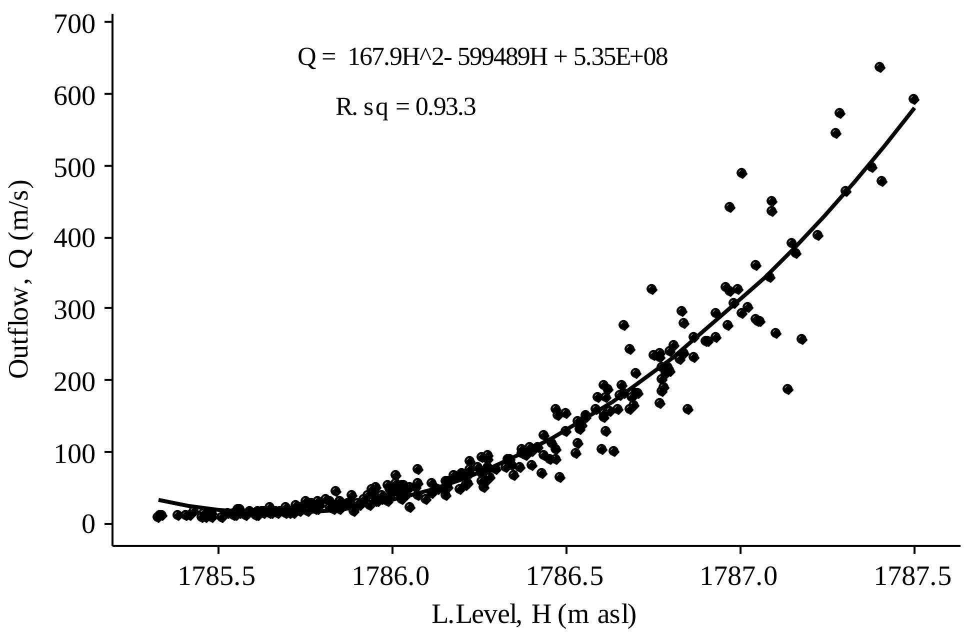
Vogel et al. (1999) have also developed and introduced a general classification system for determining whether reservoir capacity is determined by within-year or over-year behavior. They have shown that the coefficient of variation of annual inflows C_v and the standardized net inflow m, together, can be used to determine whether reservoirs tend to refill each year (within-year) or whether they are seldom full in a year (over-year).Their approximate classification criteria classifies within-year systems as systems with $C_v < 1$ and standardized inflow in the range $C_v < m < (1/C_v)$. Similarly, over-year systems are classified as either systems with $C_v > 1$ or systems with $C_v < 1$ and standardized inflow in the range $0 < m < C_v$. If we used m value alone for Lake Tana, with an m value estimated as 0.57 which is less than one and hence this indicates that the Lake has over-year storage behavior. However, if we consider the C_v as an additional criteria as indicated by Vogel etal. (1999) the Lake has a coefficient of variation of annual inflow $C_v = 0.28$ and a standardized net inflow, m=0.57. This indicates that the Lake has a within-year behavior. So it is difficult to clearly define Lake Tana's behavior with respect to within- year or over-year storage characteristics. It exhibits both characteristics.

In the absence of clear demarcation on its characteristics as either within-year or over-year storage further investigation on effects of the regulation on the characteristics of the Lake, its Outflow and Level are necessary to device a reliable method for their naturalization. Because of the change in the range of the reservoir nearly 720Mm^3 (Million meter cubic) of water has been excessively withdrew from the lake during the regulation period. This has been observed by simply comparing the Outflow in both periods. So the amount of Outflow recorded during the regulation period is more than the natural supply capacity of the lake. This has happened because the Outlet of the regulating weir has been lowered by 1m than the natural sill level and during some years in the regulation period such as in the year 2003 water from the dead storage was withdrew. Because of this mismanagement transportation in the Lake was ceased for at least two months in the year 2003. Thus the annual outflow observed during the regulation period cannot be disaggregated to monthly Outflow series and do not give any clue to reverse it into its natural condition. In such situation the Outflow need to be naturalized by some other mechanisms which will be described in the subsequent section.

In its natural condition the Lake level has fluctuated within a maximum and a minimum value of 1787.51m asl and 1785.33m asl respectively. This indicates that in its natural condition the maximum range is about 2.18m. But the regulation has changed this characteristic and makes the range to exceed the normal natural condition to a value of 3.38m. Looking further into the data shows that the regulation has actually raised the maximum Lake level by 0.47m and lowered the minimum Lake level by 0.73m. Making some assumptions and restrictions on the natural characteristics and fluctuation of the range of the reservoir is deemed to be important to reverse the observations into the natural condition. In the absence of any other additional data it may be important to assume that the maximum range will not exceed the maximum value observed during the unregulated period. The assumption here is that the Lake Level will not raise and go down beyond its natural maximum and minimum levels observed during the unregulated period. Such restrictions will simplify the naturalization process. Indeed it is a random natural process which will not be treated in such very rigid restrictions. But despite it limitation the approach is somehow reasonable. The basis for such an assumption is that the Lake will serve some regulation roles by absorbing and balancing some extreme natural conditions. Taking this natural condition as a standard scale of its normal variation an adjustment can be easily made for the regulated Lake level. The adjustment is performed by linearly interpolating or converting the observed Lake level in line of the normal natural scale of variation. It is a matter of adjusting the scale of variation and changing the range of the reservoir into its natural characteristics.

The most reasonable and practical strategy to naturalize the Outflow is to find a functional relationship between the Outflow and Lake Level observed during the unregulated natural conditions. The search for the existence of any relationship between the Outflow and Lake Level is first examined by plotting Lake Level and Lake Outflow verses time on same axes and observing the patterns.

Figure 5.2 Outflow versus Lake Level relationship



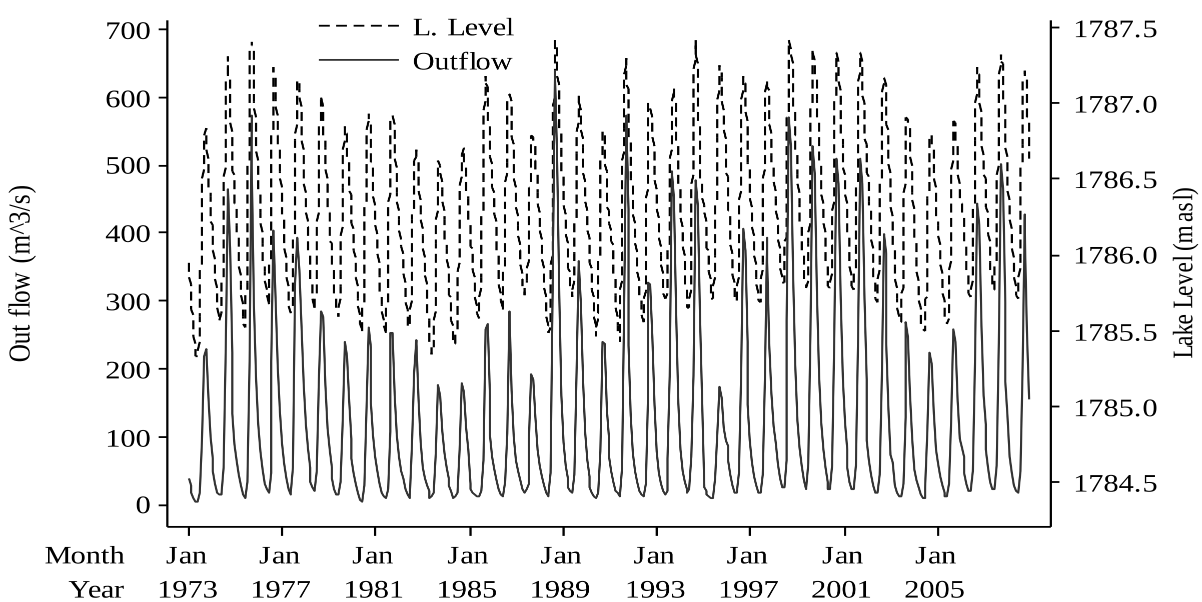
The plots have shown very clear similar patterns. The graphs are shown in Figure A1 in the appendix. This indicates the possibility of expressing this similar pattern by a mathematical model. The Outflow is then regressed with the Lake level and a new rating curve that relates the Lake Level with the corresponding outflow has been developed. The rating curve has an equation of the form:

$$Q = 167.9H^2 - 599489H + 5.35*10^8 \quad (5.2)$$

where Q is the Outflow in m^3/s and H is the Lake level in m asl and the corresponding rating curve is shown in Figure 5.2. The newly developed rating curve is used to convert the naturalized Lake Level to naturalized Outflow.

Visual inspections of the naturalized time series plots for the Lake Level and Outflow shows the need of some minor adjustments and correction on the naturalized data so that they will have and follow same pattern as data in the unregulated periods. This will complete the naturalization process and the data sets are now more or less transformed to the natural condition which can be considered for further time series analysis. Figures A2 and A3 are attached in the appendix for further visual inspection and understanding on effects of regulation and naturalization processes on Lake Level and Outflow.

Figure 5.3 Time Series Plot of naturalized Lake Level and Lake Outflow



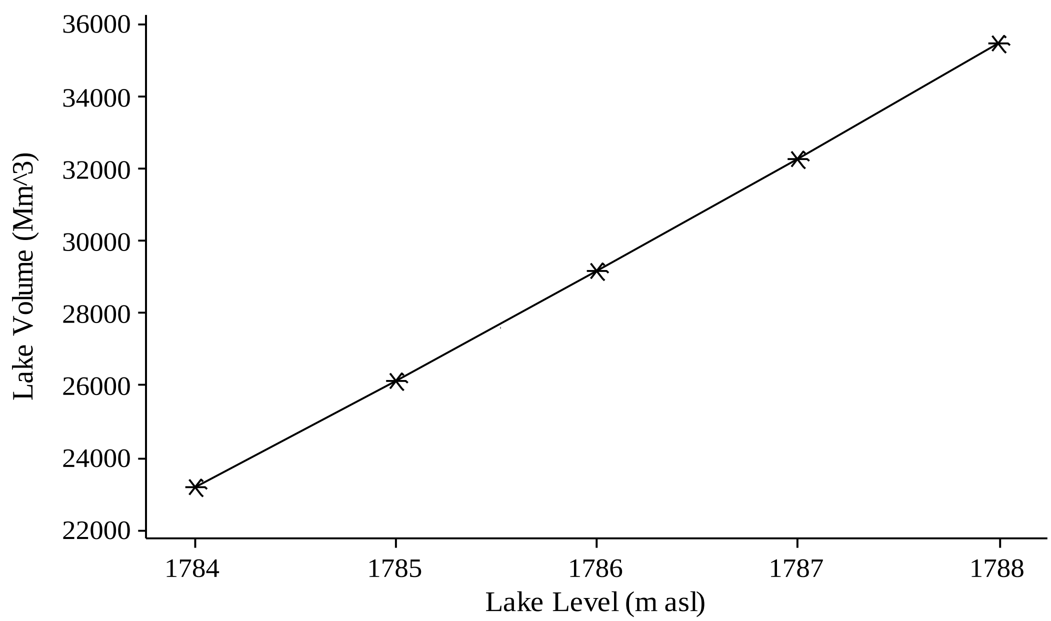
5.4. Volume Elevation relationship

Lake Tana as indicated in chapter three has an average volume of about 29Bm^3 (Billion cubic meters) of water measured at an average surface elevation of 1786m asl. The entire volume of the lake is not renewable in some reasonable period of years. The natural sill level of the Lake is at an elevation of 1785m asl and the natural maximum recorded full supply level was not exceeded 1787.51m asl. In its natural state nearly 90% of the average volume, which comprises the volume below 1985m asl, is a dead storage volume. This natural state, however, has been changed by providing a regulation weir with an out let located at 1784m asl. The intention to modify the natural outlet condition is to increase the proportion of the active storage zone while reducing the dead storage. Indeed this modification has brought an effect in changing the state of the reservoir from its natural within-year characteristics to an artificially modified over- year state. The weir regulates water storage in Lake Tana over a 3 m range from 1,784 m asl to 1,787 m asl. Thus, the zone above 1784masl may be considered as active storage. The active storage of the Lake between these levels is about 9,100 million cubic meters (Mm^3), which is approximately 2.5 times the average annual outflow from the Lake. Lake Tana bathymetry study was done by Studio Pietrangeli in1990. Elevation, volume, and area characteristics of Lake Tana take from Studio Pietrangeli (1990) are shown in the appendix in Table 16. By using these data volume versus elevation relationship is developed for the active storage. The relationship, as shown in Figure 5.4, is very linear with R^2 of 0.999 and has the form:

$$V = 3073.2 * H - 5459500.4 \quad (5.3)$$

where V is Volume of the Lake in million cubic meters (Mm^3) and H is elevation in meters above sea level (m asl).This relationship is used to compute the volume corresponding to each measured Lake level. This will lead us further to compute the net inflow based on equation 4.1. Equations 4.1 and 5.3 can be used to generate the net inflow series.

Figure 5.4 Lake Tana Volume Versus Lake Level relationship (Source:Studio Pietrangeli 1990)

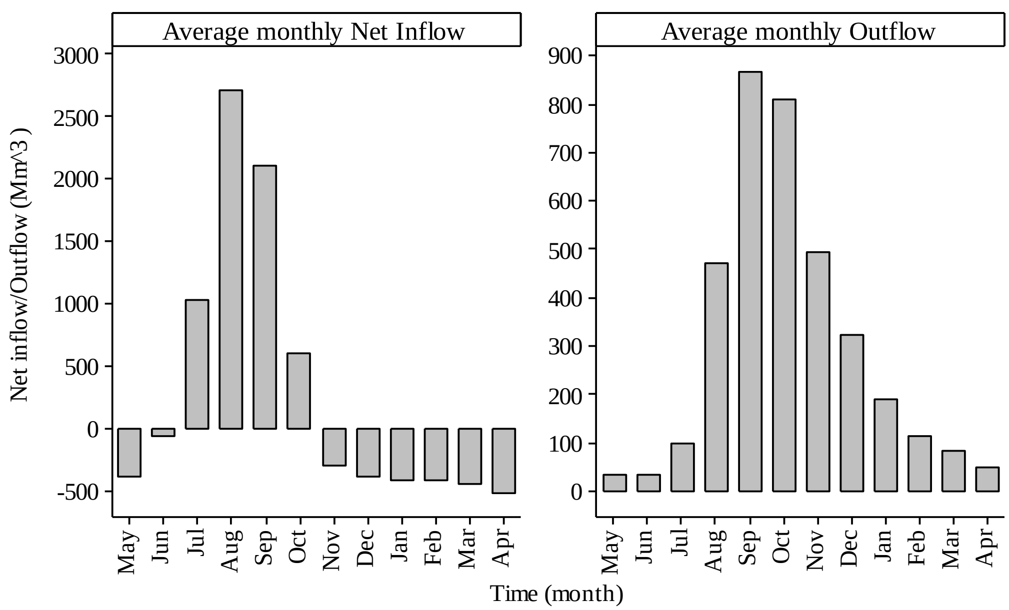


5.5. Assessing the quality and characteristics of the data sets

Hydrological time series data used for water management has to be first checked for its quality and characteristics. No matter what class of models is being entertained for modeling a given time series, the success of any modeling study is of course highly dependent upon the quantity and quality of the data. Data set may have some characteristics such as trend, periodicity or jump. The presences of outliers, trend, and the stability of variance and mean of the data sets have to be examined first before applying it to any hydrological analysis and design work.

Statistical characteristics of the outflow, Lake Level and net inflow series of Lake Tana were assessed and presented in the appendix from Table B4 to B10. For general understanding charts of average monthly net inflow and outflow, taken from the average of the data sets from 1973 to 2008 for both cases, are shown in Figure 5.5. For further understanding time series plots of net inflow series and net supply series are attached in the appendix from Figure A4 to A7.

Figure 5.5 Chart of Average monthly Net Inflow and Outflow in the years 1973-2008



5.5.1. Outlier detection

The presence of extreme values or outliers is easily detected in a graphical display of the data. Wilcox (2009) has indicated the importance of box plot in assessing the existence of outliers. Hence, the presences of outliers for the selected Lake Level and Lake Outflow records are assessed using box plot that show the absence of outlier in both data sets. The Box plots for both Lake Outflow and Lake Level are shown in the Figures 5.6 & 5.7.

Figure 5.6 Boxplot of monthly Outflow series

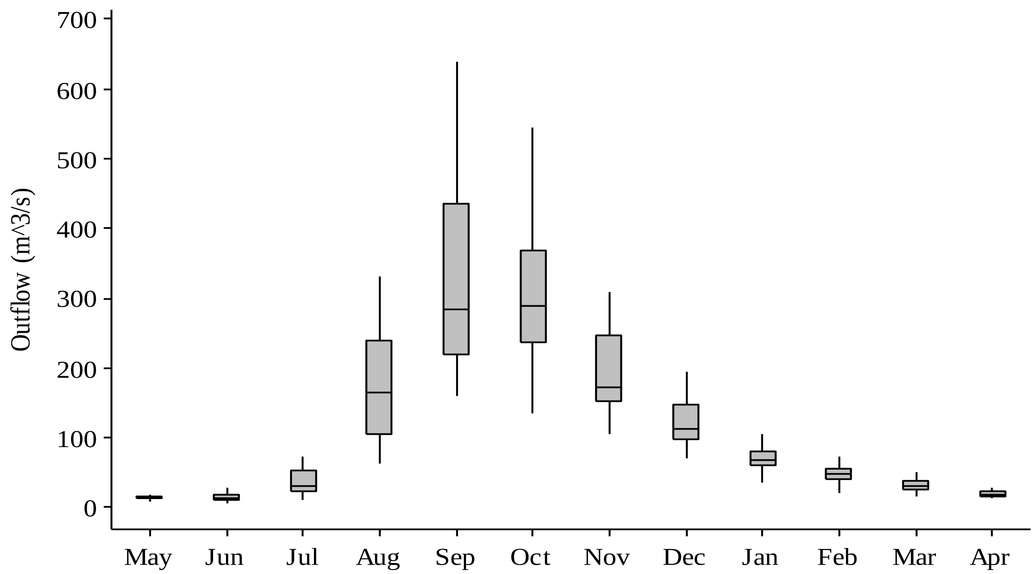
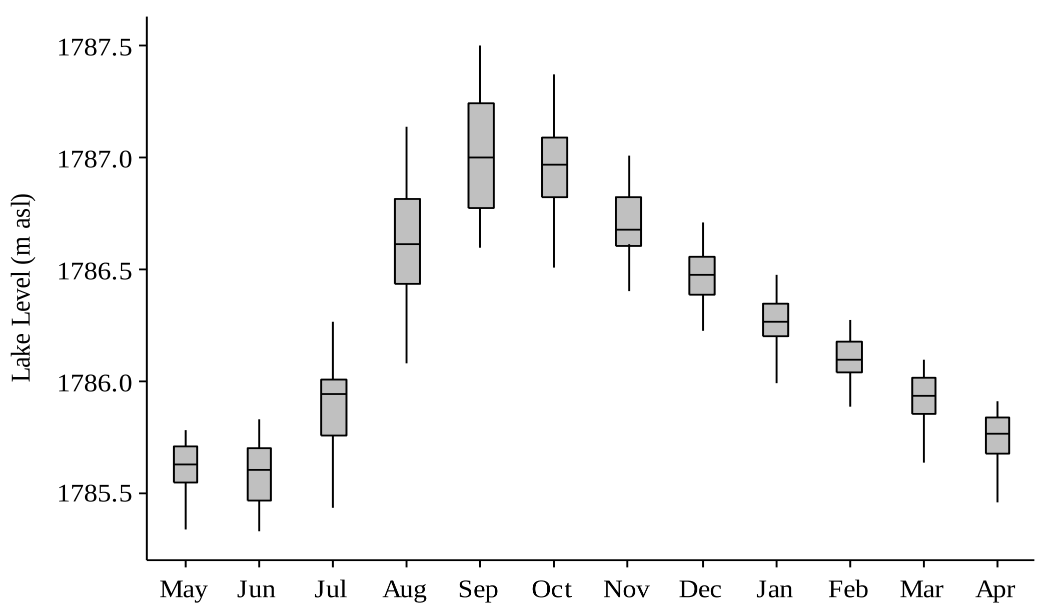


Figure 5.7 Boxplot of Lake Level



5.1.1. Trend analysis for the naturalized Lake Outflow and net inflow data

Dahmen, E. R.; Hall, M. J. (1990) have recommended the use of Spearman's rank-correlation method to investigate the presences of linear trends as it is simple and distribution-free. They have also pointed out its wide range of applicability with nearly uniform power for linear and non-linear trends. This method is used to investigate the presence of linear trends in Lake Tana net supply and net inflow time series data sets. The method is based on the Spearman rank-correlation coefficient R_{sp} which is defined as:

$$R_{sp} = 1 - \frac{6 * \sum_{i=1}^{n} D_i^2}{n\,(n * n - 1)} \qquad (5.4)$$

where n is the total number of data, D is difference, and i is the chronological order number. The difference between rankings is computed with:

$$D_i = k_{xi} - k_{yi} \qquad (5.5)$$

where K_{xi} is the rank of the variable x which is the chronological order number of the observations. The series of observations y is transformed to its rank equivalent K_{yi} by assigning the chronological order number of an observation in the original series to the corresponding order number in the ranked series y. If there are ties, i.e. two or more ranked observations y with the same value, the convention is to take K_{xi} as the average rank. One can test the null hypothesis, Ho: R_{sp} = O (there is no trend), against the alternate hypothesis, H_1: R_{sp} < > O (there is a trend), with the test statistic:

$$t_t = R_{sp}\left[\frac{n-2}{1-R_{sp}^2}\right]^{0.5} \qquad (5.6)$$

Where t_t, has Student's t-distribution with v = n-2 degrees of freedom. At a significance level of 5 percent (two-tailed), the two-sided critical region, U, of t_t, is bounded by:

{- ∞, t {v, 2.5%}}U {t {v, 97.5%}, +∞)

And the null hypothesis is accepted if t_t is not contained in the critical region. In other words, the time series has no trend if:

t {v, 2.5%} < t_t < t {v, 97.5%}

The method has been used to investigate the presence of trend in the both the net supply and Net inflow series. To make the assessment first the series of the required variable for example net supply or net inflow of identical months in the record period has been created. This is done to examine the change in the corresponding identical months i.e. to make comparisons of January to January, February to February and so on. After rearranging the data series in the required format, the test statistics for all months have been computed using equations 5.3 to 5.5. The test statistics for the lake outflow shows that the absence of trend for all months except for the month of May and June. The case of May and June may be associated with the rating curve used for naturalizing the regulated Outflow. Because the quadratic equation used to convert Lake Levels to Outflow has some level of inaccuracy in a region near to its turning point. Otherwise these two months are known with having very low outflow which will have very little chance for them to show such kind of changes in their characteristics that can be explained by change of some physical processes which drive them. Summary of the test result is presented in the appendix from Table B11 to B12.

The test statistics for the lake annual net inflow series t_t is 1.307 which is less than the student's t distribution critical value of 2.032 for 34 degree of freedom and 95% significance test for all months. This indicates the absence of sufficient statistical reason for the presence of trend in the annual net inflow series. So it can be considered as trend free series. Further trend assessment has been also made for the monthly net inflow series using the same method. The evidence available is not sufficient to conclude that there is a trend in all the months i.e. the absence of sufficient statistical justification for the existence of trend in all months except December. The net inflow positive trends observed in December may be associated with some data acquisition and processing errors. Otherwise it is hardly possible to justify the existence of trend in this month alone.

5.1.2. Assessing the stability of net inflow mean and variance

In addition to testing the time series for absence of trend, one must test it for stability of variance and mean. Assessing the stability of variance and mean is very essential and critical in time series analysis especially in the analysis of stationary time series. The net supply and inflow time series are deemed to be used for further time series analysis and simulation. Before applying time series analysis and modeling techniques, checking the stability of means and variances of the series are very necessary. Stability of variance and mean for the net supply series has been assessed using the procedures outlined in Dahmen, E. R.; Hall, M. J. (1990). The test statistic for assessing the stability of variance is the ratio of the variances of two split, non-overlapping, sub-sets of the time series. The assessment involves the use of F-distribution. The distribution of the variance-ratio of samples from a normal distribution is known as the F, or Fisher, distribution. Even if the samples are not from a normal distribution, the F-test will give an acceptable indication of stability of variance. Thus, the test statistic reads:

$$F_t = \frac{\sigma_1^2}{\sigma_2^2} = \frac{s_1^2}{s_2^2} \qquad (5.7)$$

where s^2 is variance. The null hypothesis for the test, $H_0: s_1^2 = s_2^2$, is the equality of the variances; the alternate hypothesis is $H_1 : s_1^2 <> s_2^2$. The rejection region U is bounded by:

$\{O, F\{v_1, v_2, 2.5\%\}\} U \{F\{v_1, v_2, 97.5\%\}, +\infty\}$

where $v_1 = n_1 - 1$ is the number of degrees of freedom for the numerator, $v_2 = n_2 - 1$ is the number of degrees of freedom for the denominator, and n_1 and n_2 are the number of data in each sub-set. In other words, the variance of the time series is stable, and one can use the sample standard deviation s as an estimate of the population standard deviation σ if:

$F\{v_1, v_2, 2.5\%\} < F_t < F\{v_1, v_2, 97.5\%\}$

The assessment for stability of mean involves the use of t-distribution. The t-test for stability of mean requires computing and then comparing the means of two or three non-overlapping sub-sets of the time series (the same subsets from the F-test for stability of variance can be used also to examine stability of mean). A suitable statistic for testing the null hypothesis, $H_0: \bar{x}_1 = \bar{x}_2$, against the alternate hypothesis, $H_1: \bar{x}_1 <> \bar{x}_2$, is:

$$t_t = \frac{\bar{x}_1 - \bar{x}_2}{\left[\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} * \left(\frac{1}{n_1} + \frac{1}{n_2}\right)\right]^{0.5}} \qquad (5.8)$$

Where n is the number of data in the sub-set, $\bar{x}$ the mean of the sub-set, and s^2 its variance. In samples from a normal distribution, t_t, has a Student t-distribution. The graphical test is the most commonly used test for testing the hypothesis that a given time series is normal. In this test, the empirical distribution of the series is plotted on normal probability paper to determine whether the plotted points can be approximated as a straight line. Normality test for Lake Tana Outflow and net inflow for each month has been done and proven that all seasonal data series follows a normal distribution. For t_t, the two-sided critical region, U, is:

$\{-\infty, t\{v, 2.5\%\}\} U \{t\{v, 97.5\%\}, +\infty\}$

With $v = n_1 - 1 + n_2 - 1$ degrees of freedom, i.e. the total number of data minus 2. If t_t is not in the critical region, the null hypothesis, $H_0: \bar{x}_1 = \bar{x}_2$ is accepted instead of the alternate hypothesis, $H_1: \bar{x}_1 <> \bar{x}_2$. In other words, the mean of the time series is considered stable if:

$t(v, 2.5\%\} < t_t < t(v, 97.5\}$

The analysis is carried out by dividing the recorded period i.e. the period from 1973 to 2008 into two equal parts. The variance and mean for each month in each category is calculated and then the F_t and t_t are determined using equation 5.6 &5.7 respectively. Using the F and t-distributions results are summarized and presented in the Table B13 in the appendix.

The taste statistics for stability analysis of mean and variance of the net supply series shows that there is not sufficient statistical evidence to assume that the mean and variance of the series are instable. In view of this, the testes for trend and the assessment made on mean and variance stability can be taken as an initial clue for assuming the net supply and associated net inflow series are stationary. This assumption will actual be re-evaluated and confirmed later during the model diagnostic stage.

5.1.3. Analysis of Periodicity

Trend and seasonality are usually detected by the time sequence plot of the series. As it is shown in the time series plot and bar charts in Figures A4, A7, and A8 in the appendix there is a clear seasonality in both the outflow and net inflow series. The seasonal part can be represented by mean of each month. This will be explained further in chapter six. In summary the data manipulation shows that the net supply and net inflow series can be considered as data set generated from stationary stochastic processes from normal distributions.

5.2. Water demand data

The most significant water demands from Lake Tana are the demand for energy production and environmental release. The Ethiopian Electric Power Corporation (EEPCO) is the responsible organization for operating the Lake and managing the collection and distribution of related data. Basically it collects and records data on a daily basis on the amount of energy produced, the corresponding amount of water used for its production and other hydrological data such as Lake Level. The release from Lake Tana for energy production is obtained from EEPCO records. EEPCO used numeric conversion factor to estimate discharge from the power produced. The energy and discharge data recorded since the operation of Tana-Bales hydro-electric station have been collected and examined for further analysis. Since an artificial outlet and water way has been provided for the purpose of taking water for the newly constructed Tana Belese power plant station the amount of water that would have been flown to the natural out flowing river has been affected. SMEC (2008c) and McCarty (2010) have made studies on the minimum amount of environmental flow required in the natural outflow course from the Lake and estimated as $17m^3/s$ and $19.88m^3/s$ respectively. Based on these studies approximately a constant release of $20m^3/s$ is considered for environmental flow to the natural out flowing river during the non spill period. Average monthly demand for energy production and environmental flow is shown in Table B14 in the appendix.

6. Application of Stochastic Analysis, Modeling, and Simulation Techniques in Planning and Managing Lake Tana's Sub Basin Water Resources Systems

6.1. Introduction

The overall outcomes and consequences of Lake Tana's water resources systems planning and management attempt can be evaluated by assessing the performance measuring indices of Lake Tana in view of various alternative development scenarios. As it is discussed in chapter four there are two alternative approaches to assess the indices: the net inflow approach and the net supply approach. In both approaches stochastic analysis, modeling and simulation techniques can be employed to assess Lake Tana's responses to various alternative development scenarios in its sub basin. The net inflow approach involves the computation of change in storage which is done by using the lake level data. In Lake Tana a 10cm depth of water, measured from its top surface area, represents an equivalent volume of nearly 30million cubic meters (Mm^3) of water which is almost equal to the entire flow in the month of May. So a small error in Lake Level computation has a significant effect on other values that depend on it. Unlike the net inflow, the net supply can be obtained and used directly with very little efforts in its processing and systematization. Though both the approaches are conceptually clear and theoretically acceptable only the net supply approach is illustrated here because of its computational efficiency. Hence, the stochastic nature of the net supply series is investigated first and then applied latter in examining various alternative development scenarios of Lake Tana's water resources systems.

Vogel and Stedinger (1988) have emphasized the importance of using stochastic streamflow models and synthetic streamflow sequences in the design of storage reservoirs. Wurbs and Bergmans (1990) have also commented that the stochastic nature of streamflow and other pertinent variables must be reflected in methods for quantifying storage related variables. This involves searching an appropriate stochastic models followed by synthetic generation and simulation tasks. The attempt to model the net supply series is first begin by preparing the monthly net supply series in a suitable manner to the intended purpose. Development of a complete homogeneous set of streamflow data represents a large portion of the total effort of modeling task. As it is discussed thoroughly the gauged monthly net supply have been naturalized to remove nonhomogeneities caused by the regulation effect and the naturalized net supply series is further assessed for the existence of trend, seasonality, jump and also for stability of mean and variances. In general the data manipulation dealt in chapter five has revealed that the net supply series has no any significant trend and jump and also it can be consider as a stationary series. However, it possesses seasonality which can be identified clearly by visual inspection of its autocorrelation plots shown in Figure 6.1.

Hipel et al. (1994) have indicated the usefulness of employing deseasonalized models for times series in which the mean and variance within each season are stationary across the years. As it is already expressed in chapter five the monthly mean and variance of the net supply are stable i.e the series is stationary. This shows the possibility of fitting deseasonalized model to the series in which its seasonal component has been removed first. The usual procedure in removing the seasonal component involves subtracting the seasonal mean from each series and dividing this by the seasonal standard deviation. The deseasonalization process makes the series a standardized net supply series. Figure 6.2 shows the deseasonalized or standardized net supply series. The probability distribution type of the standardized series has to be identified first before running to model identification and calibration processes. Usually the series is assumed to follow a normal distribution if not a proper transformation is applied to approximately transform the series into normal distribution. Fortunately, the standardized series follows a normal distribution as shown in Figure 6.3. Now a time series model can be fitted to the standardized series. Subsequently, the most appropriate nonseasonal ARMA model will be identified for fitting to the resulting standardized series. The following sections deals with the model development processes.

Figure 6.1 Autocorrelation Function for monthly net supply series
(with 5% significance limits for the autocorrelations)

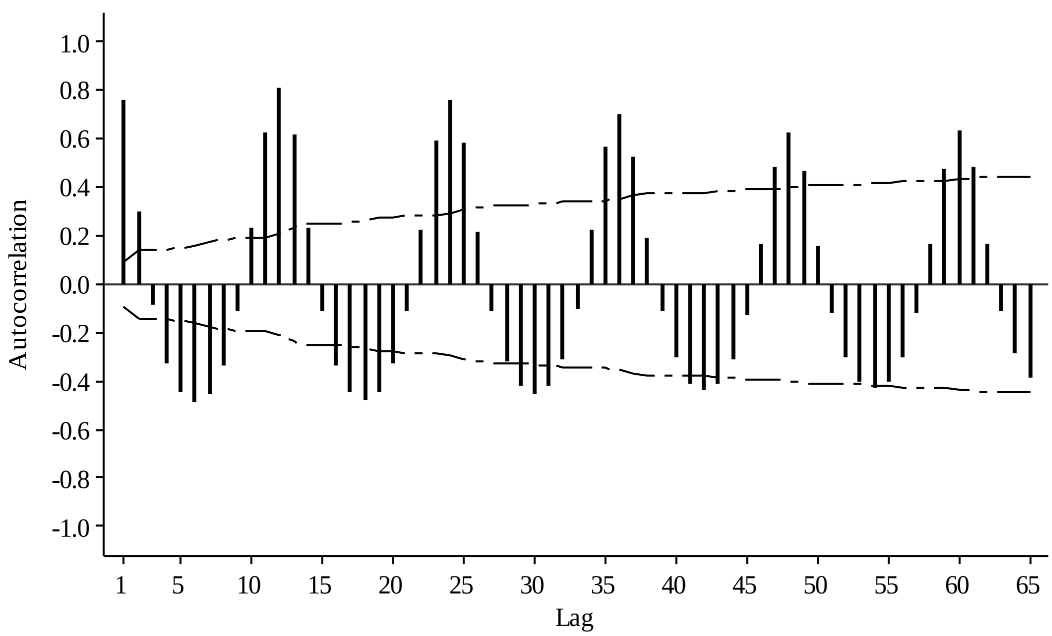


Figure 6.2 Time Series Plot of Standardized net supply

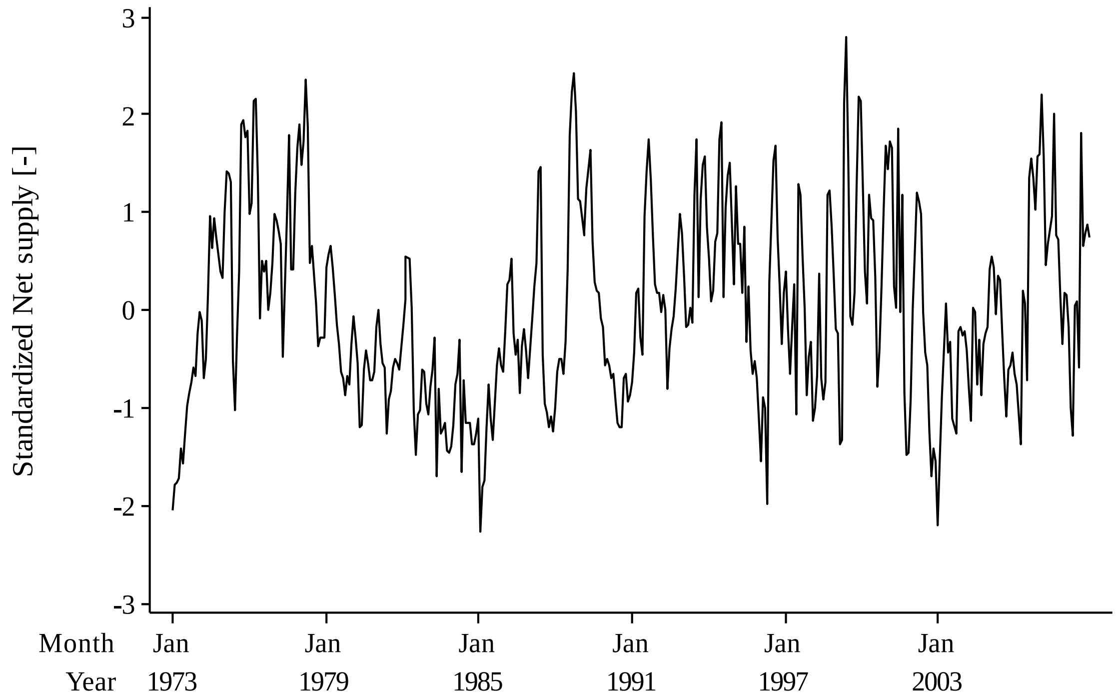
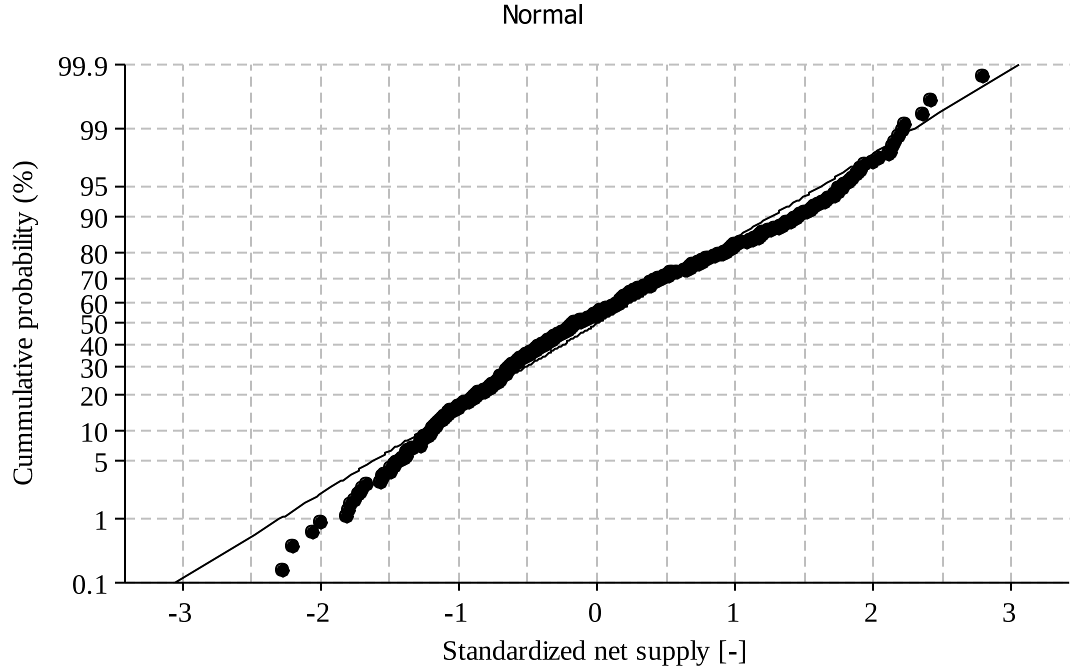


Figure 6.3 Probability Plot of standardized net supply series
Normal



6.2. Model identification, calibration and diagnostic check

When modeling stochastic process using a given data set a large number of models are often available for consideration. The purpose of the identification stage is to ascertain the subset of models that appear to hold more promise for adequately modeling the time series. The sample autocorrelation and partial autocorrelation functions are the most commonly used tools to identify the families of models that seem appropriate for initial consideration. Sample Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) for the standardized net supply series are shown in Figures 6.4 and 6.5 respectively. The following general characteristics of the ACF and PACF may be invoked in model identification.

1) When the series is white noise, the estimated values of ACF and PACF are not significantly different from zero for all lags.
2) For a pure AR model, the sample ACF attenuates and does not appear to cut off while the sample PACF truncates and is not significantly different from zero after lag p.
3) If the sample ACF truncates and is not significantly different from zero after lag p but the PACF attenuates and does not appear to cut off, this may indicate that MA model is preferable.
4) If both the sample ACF and PACF attenuates ARMA model may be employed.

Figure 6.4 Autocorrelation Function for Deseasolized net supply series
(with 5% significance limits for the autocorrelations)

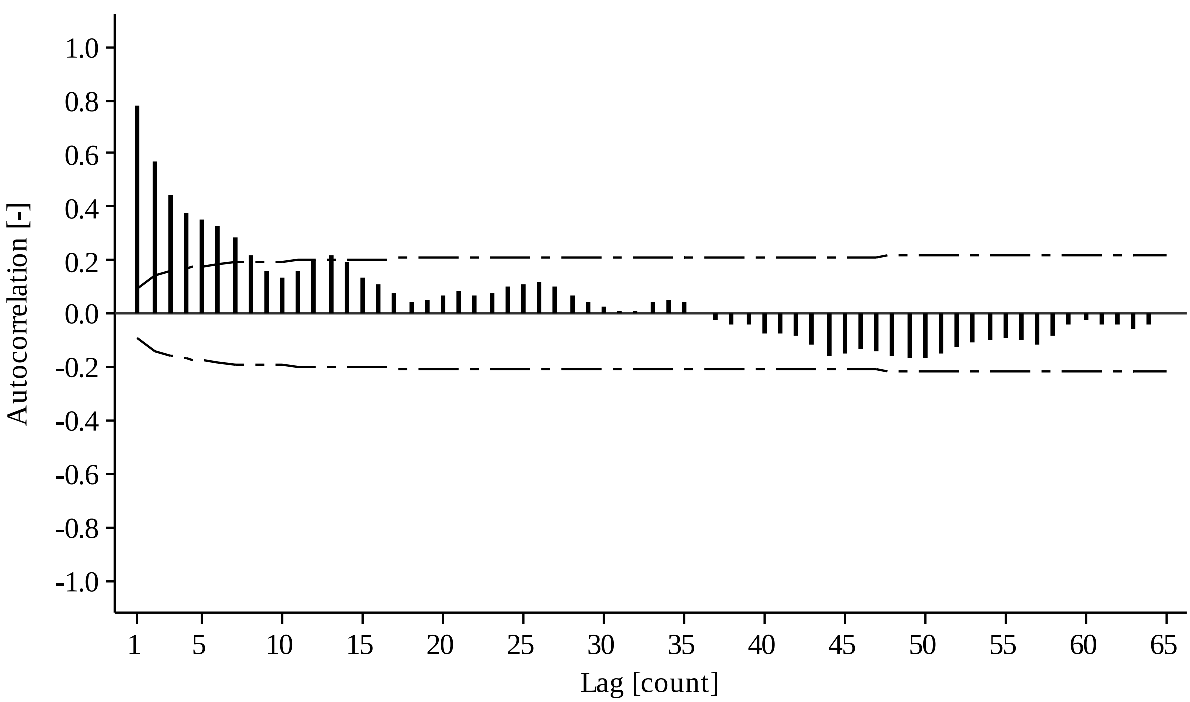
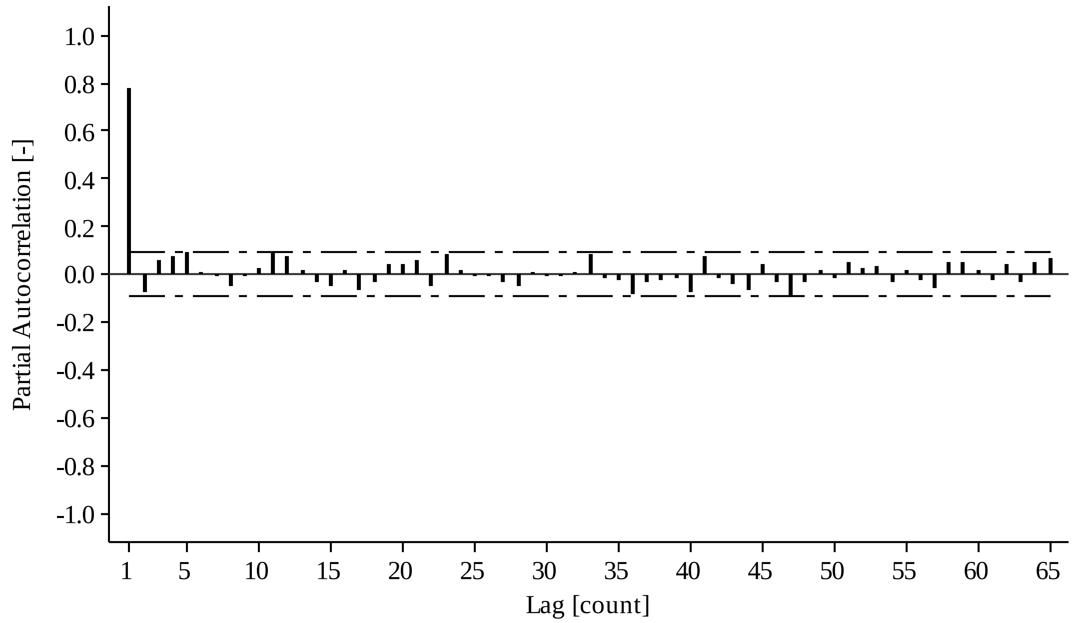


Figure 6.5 Partial Autocorrelation Function for Deseasolized net supply series
(with 5% significance limits for the partial autocorrelations)



The general guidelines outlined above in conjunction with the examination of Figures 6.4 and 6.5 indicate AR (1), model is initially appeared as appropriate to fit the deseasonalized net supply series. Using MINITAB version 16 statistical software the parameters for the chosen AR (1) model have been estimated. To ensure the adequacy of the model in describing the time series under consideration, graphs of Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of the residual have been plotted and examined. The principal assumption in time series modeling is whiteness and normality property of the residuals i.e. they are white noise (uncorrelated) series following a normal distribution.

The RACF and RPACF, in Figures A8 and A9 in the appendix, reveal that the chosen model satisfies the whiteness assumption for the deseasonalized net inflow series of Lake Tana. The assumption of normality for the residuals of the fitted AR (1) model is ascertained by performing a normality test using the MINITAB version 16 statistical software. MINITAB performs normality test using probability plot of the data series. If the plot resembles approximately a straight line it shows that the data set follow a normal distribution. Probability plot of the residual, shown in Figure A10 in the appendix, shows that the series can be approximated by a random process from a normal distribution.

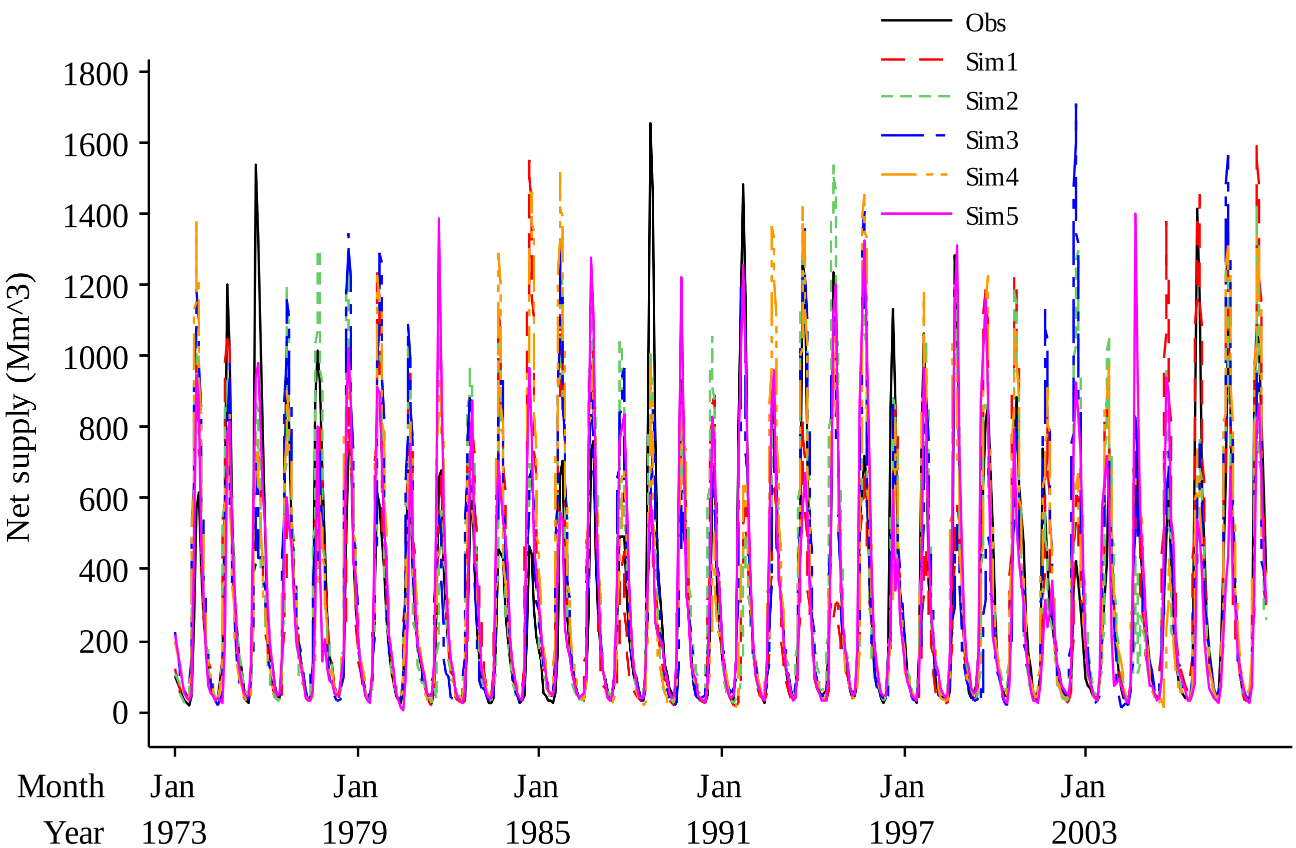
Finally a first order autoregressive model with model parameters $\emptyset_1 = 0.7845$ and $\sigma_a = 0.612$ is identified as an adequate model to represent the standardized series of the net supply from Lake Tana sub basin. The model will have the form:

$$z_t = 0.7845 z_{t-1} + a_t \qquad (6.1)$$

Where z_t and z_{t-1} are the standardized synthetic generated values at time t and t-1 and a_t is a random number with mean zero and standard deviation of 0.612 generated from a normal distribution. In using the model a starting value is required. Indeed any value can be used as a starting value and its effect will die v quickly in the generated series. But it has to be noted that the first portion of the series perhaps half of its length has to be ignored to remove the effect of the starting value. For this purpose generating a very long enough synthetic series is advisable.

In order to convert the synthetic generated standardized series into its corresponding seasonal net supply series an inverse standardization has to be invoked. This can be done by multiplying the synthetic standardized series by the seasonal standard deviation and adding the season mean. This will complete the generation of synthetic net supply series which can be used for further analysis and design purposes. For visual inspection and understanding plots of the observed and synthetic generated (simulated) series are show in Figure 6.6.

Figure 6.6 Time Series Plot of Observed and simulated net supply series



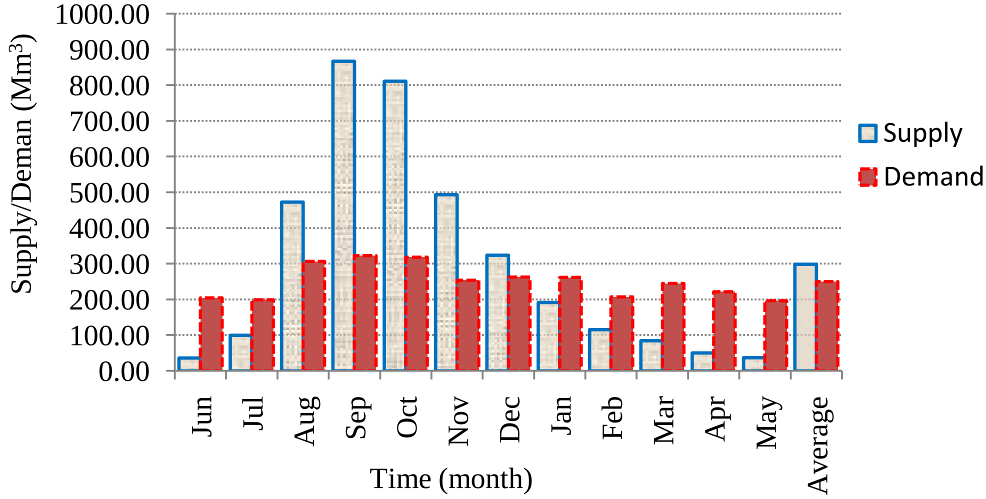
6.3. Model application

6.3.1. Determining minimum operating Level of Lake Tana

Among the various primary services offered by Lake Tana, supplying water to Tana-Beles hydropower plant and serving as means of transportation are the two most important sectors that need prior consideration in its development and operation management plans. As it is discussed thoroughly in chapter four, the whole catchment including the Lake area is represented by an equivalent catchment with an average annual net supply capacity of 3632 Million cubic meters (Mm^3). This conceptualization will help us to simplify the situation and easily understand the problems. It has an advantage to consider, evaluate and understand all possible development alternatives easily and quickly from their initial stage to their maturity level. For example in such conceptualization it is possible to investigate the need for storage and also to compute its required volume, just at the outlet of the sub basin where the Lake is situated, to balance the supply capacity of the equivalent catchment and any anticipated demand.

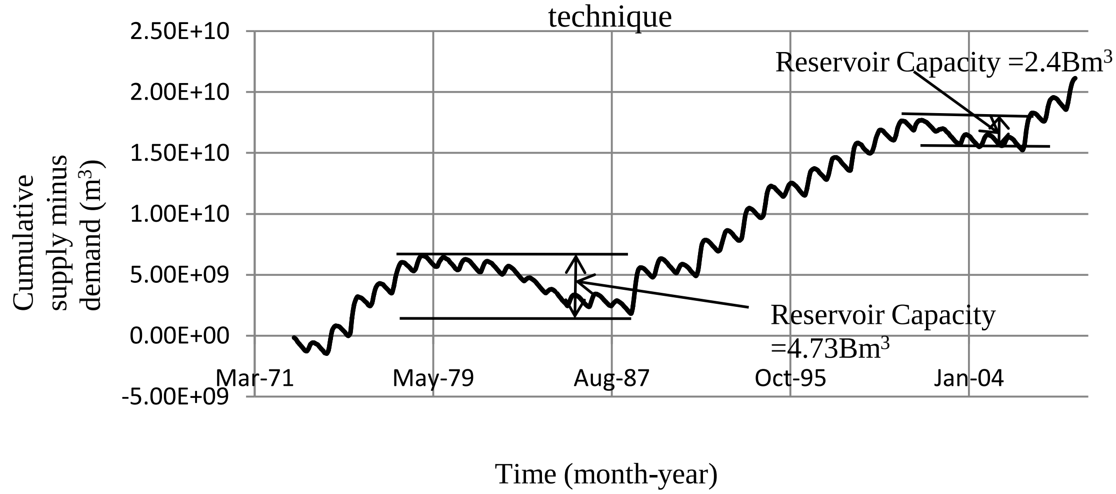
In its existing conditions and perhaps for some reasonable future time the main water demands at the outlet of Lake Tana are the demand for Tana Beles hydropower plant and the release required for environmental flow in its natural out flowing river. Tana Beles hydropower plant needs an average supply of $77m^3/s$ (SMEC 2008c). The hydropower plant is situated in another adjacent basin called Beles. This makes an inter basin transfer of water from Tana to Beles basin. Prior to the development of this hydropower plant water from the Lake has only one natural outlet. The newly added artificial outlet from the Lake to the adjacent basin has reduced the outflow amount through the natural outlet. It is therefore required to make an estimate for the minimum environmental flow that needs to be maintained in the natural out flowing river. Following the regulation of the Lake outflow and the provision of the additional artificial outlet, an estimate for the environmental flow using the Desktop Reserve Model (DRM) has been made by McCartney et al. (2010).The study indicates the need of allocating 22% of the natural mean annual flow to environmental flow. SMEC (2008b) have also presented summarized result of other studies and indicates the need of releasing a fixed regular flow of $17m^3/s$, which is approximately equivalent to 22% of the average hydropower demand, during the non spill period for environmental flow. Based on these estimates $20m^3/s$ is assumed as environmental flow for all the periods except for the periods when the reservoir is full and spilled over. Hence, the total average annual demand i.e. the demand for hydropower supply and the release for environmental flow is estimated as $3000Mm^3$. On annual basis the average annual net supply is greater than the average annual demand. The average annual demand is nearly 83% of the average annual net supply. But when we look the monthly distributions of both the supply and the demand as shown in Figure 6.7 there are some months in which the demand is greater than the supply. These mismatches require the provision of an adequate storage reservoir.

Figure 6.7 Charts of average monthly Supply and Demand volumes



The active volume required to balance the supply and demand is estimated using the sequent peak technique for over year storage as shown in Figure 6.8 using the historical monthly Outflow (net supply) time series. Consequently, an active storage volume of 4.73 Billion meter cubic (B m^3), which is the maximum of the two estimated active storage volumes, is required to effectively balance the mismatches in demand and supply.

Figure 6.8 Reservoir capacity determination using sequant peak technique



The purpose of accomplishing the redesign task is to get know how on the rationale behind the modification of the natural condition during the construction of the regulation weir. Following the estimation of the required active volume critical investigation is carried out to find a proper storage space for its storage. It should be noted that the estimation is done based on the ideal assumed condition using an equivalent catchment concept. But in reality there is a Lake at the place where storage is intended to be created. At Lake Tana's average surface area the additionally required active volume needs a depth of 1.55 m. So the concern is to find an appropriate space for the additionally required active volume. Further investigation and understanding is required to find way out on how to adjust the ideal condition with the reality.

Understanding the actual existing condition of the Lake is very important to devise a mechanism that enables us to incorporate the additional active volume into the existing situations without bringing any other undesirable effects. One of the most important thing that need to be considered in finding a storage space for the additional active volume in Lake Tana is the problem of flooding in areas around the Lake. Inundation of part of the floodplains around Lake Tana is a regular phenomenon during the rainy season. Affected areas are mainly the Fogera (eastern part of the Lake), Dembia(northern part of the Lake) and Gilgel Abbay(southern part of the Lake) floodplains. Among the main causes for flooding in these areas, bank over flow and backwater flow from the Lake, are the two most significant factors that complement each other. After the construction of the Chara-Chara weir the Lake Level was raised and a level which was not observed in the past has been observed. Local farmers mentioned that bank overflow and the severity of flooding in these areas have increased after the construction of the Chara-Chara weir (SMEC 2008b). Actually this might have been happened because of poor reservoir operation and management practices. So, because of flooding the Lake level cannot be raised beyond its historic maximum water level of 1787.5m asl as it has a practical testimony that cannot be compromised. The proper space for the required active storage is, therefore, found not by raising the Lake level further beyond its natural maximum level but it is only possible by changing portion of the Lake dead storage into an equivalent active volume. The natural average minimum water level of the Lake is about 1785.56m asl. In its natural condition the volume below 1785.56m asl can then be considered as dead storage. For the purpose of accommodating the additional required active volume the portion of the dead storage of the Lake is changed to an active volume by lowering the Outlet of the regulating weir by an amount equal to the depth of the additional active volume. This has led to the change of the natural sill level from its 1785m asl to 1784m asl. Indeed the reason for setting the Outlet level of the regulating weir to an elevation of 1784m asl is now clear and justified in such a way that it is because of the necessity to get an adequate volume for the additionally required active storage to balance the supply and demand.

The natural average maximum water level of the Lake is about 1787.03m asl. This indicated that in its natural state the lake is serving as a reservoir with an operating range of 1.47m ranging from 1785.56 to 1787.03m asl. However, this was not sufficient enough for balancing the supply and demand mismatch. Thus an additional active volume depth of 1.55m is required and created by changing the portion of naturally occurring dead storage volume into an active volume as described above. To maintain the natural maximum level of the Lake the crest level of the regulating weir is situated at an elevation 1787m asl. In the artificially modified condition the Lake is being operated in the range from 1784m asl to 1787masl.

As it is indicated above the Lake is used for both transportation and supplying water for hydropower generation. From hydropower supply perspective the minimum outlet level has been located at an elevation of 1784m asl. However, this does not meet the minimum water level requirement for navigation purpose. The minimum Lake level required for navigation purpose is 1784.75m asl. Below this level transportation will cease as it has been happened in the year 2003. Operating the Lake level below 1784.75m asl will bring a tradeoff between hydropower supply and navigation service i.e. the active volume between 1784m asl and 1784.75m asl has a conflict between hydropower supply and navigation. One way of handling this conflict is to find a minimum operating level in a win-win approach. Meaning finding an acceptable minimum operating level that treats both services equally. This minimum operating level can be obtained by simulating the Lake at various operating levels taken in the conflict region of the active volume and determining the corresponding reliabilities for both services. For this purpose simulation runs using synthetically generated net inflow supply series has been carried out at operating levels of 1784m asl, 1784.2m asl, 1784.4m asl, 1784.6m asl and 1784.8m asl. Using the fitted AR (1) model synthetic monthly net supply series have been generated. The synthetic monthly net supply series, which is considered as inflow for the equivalent catchment, are routed through the reservoir with a specified storage volume $S_{(t)}$ and demand $D_{(t)}$ as:

$$
\begin{aligned}
&S_{(t+1)} = S_{(t)} + Q_{(t+1)} - D_{(t+1)} \\
&S_{(t+1)} < 0 \Rightarrow S_{(t+1)} = 0 \\
&S_{(t+1)} > S_{\max} \Rightarrow S_{(t+1)} = S_{\max}
\end{aligned}
$$

where S(t) is reservoir storage at the beginning of time step t, Q(t) is inflow to the reservoir in time step t, D(t) is demand from the reservoir in time step t and S_{max} is the reservoir storage capacity. Surplus water is spilled and the reservoir is assumed to be full at the beginning of each simulation. The water demand is specified on monthly basis and each synthetic generated time series of monthly Outflow is routed through the reservoir and the number of failure months is recorded. This simulation run is easily and conveniently done using Microsoft office excel spreadsheet.

The procedure follows:

a) Identify, estimate and validate stochastic stream flow model.

b) Generate different realization of a synthetic time series of monthly runoff of historical length.

c) Route the synthetic time series through the reservoir with specified storage volume and water demand.
d) Estimate Reliabilities of Lake supply capacity for Tana Beles hydropower and its navigability

During simulation runs, assuming the reservoir starts full, the reservoir contents are simulated over 50 different synthetic realizations of each 36 years period. Whenever the reservoir contents plus inflow in a given period are insufficient to satisfy the demand D for the hydropower and environmental flow at that period, i.e. when the Lake level is below the chosen operation level, a failure is documented and the amount required only for environmental flow is released. If the reservoir contents plus the inflow minus the demand in a given period were greater than the storage capacity S, i.e. if the reservoir level is above 1787m asl, the extra water over the storage capacity is allowed to spill over. Beside, in any simulation run the period with a Lake level below 1784.75m asl is treaded as failure from navigation requirement perspective. For the chosen demand values and operation levels the corresponding reliabilities for supplying the Tana-Beles hydropower project and transportation services are estimated. The reliabilities are estimated using:

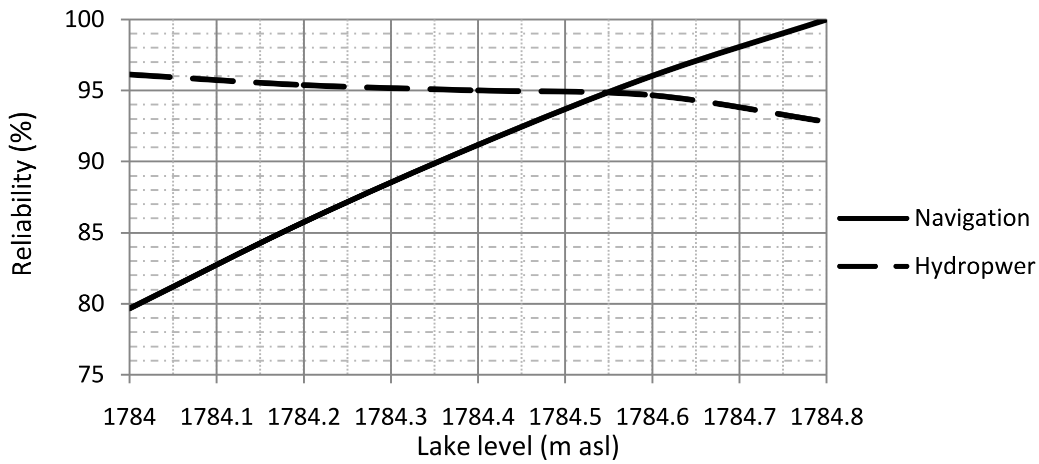
$$R = [1 - (F/N)] * 100$$

Where R is the reliability of reservoir supply or navigation service, F is the number of failure (number of months when the release is less than the required demand or the Lake level is below 1784.75masl). N is the number of periods (months) used in the simulation analysis.

Plotting the reliabilities of both services versus operating level on the same axes makes the reliability curves to intersect each other. The Lake Level at the intersection point of the reliability curves is the minimum operating level that treats both hydropower supply and navigation services equally. Figure 6.9 shows plots of hydropower and navigation reliabilities versus operating level on same axes. The intersection point of the reliability curves shows the minimum viable operating level of the Lake. At this minimum operating level both the sectors can be treated equally. Thus operating the Lake at a minimum operating level of 1784.55m asl has equal effect for both Tana Beles hydropower plant supply and Lake transportation. In the absence of any other techniques and in view of the difficulty in expressing some social values offered by the Lake such simple approach is highly important and can be used as a basis for further decision making and alternative comparisons.

Operating the Lake above or below this level has a trade off between these two services. It is not an optimal minimum operating level but it is a level that treats both services equally and can be considered as a reference for further decision making. The author wants to note that, by operating the Lake level below 1784.55m asl, the gain in hydropower supply reliability as the expense of transportation reliability is very small and hence not advisable in any ways.

Figure 6.9 Plots of Reliabilities versus operating levels



6.3.2. Estimating safe yield of Lake Tana

Safe yield or firm yield is defined as the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the hydrologic period of record (Wurbs, 1990). Precise text book definitions of firm yield can be formulated for a simple river basin with a single reservoir and single water use. However, in actual practice, for a complex multiple reservoirs, multiple user, river basin system, Wurbs (1990) has indicated that firm yield and yield versus reliability relationships must be defined in terms of basic assumptions and approaches used in handling various complicating factors. Likewise, the firm yield for Lake Tana is defined as the maximum withdrawal rate from the Lake which can be maintained in all the times at its desired minimum operating level. A portion of the release is used to meet the requirement for environmental flow and the remaining is supplied to the hydropower plan. The implicit assumption here is that the firm yield represents the maximum potential of the Lake that can be exploited all the times at its acceptable minimum operating level with equal treatment of all the services that it offers.

Firm yield is usually computed using a reservoir system simulation model. For a given reservoir storage capacity and inflow sequences, the system is simulated with alternative trial demand levels in an iterative search for the demand level which just change the storage capacity to the minimum operating Level. The average annual and corresponding monthly releases, which were used in determining the additional active storage required and the minimum operating level, have been reduced by different factors and used here for estimating the safe yield. Following similar simulation procedures as described above the safe yield of the Lake has be estimated as 51m^3/s. This yield includes the release for both hydropower and environmental flow. The proportion of the safe yield that accounts for hydropower supply is about 31m^3/s which is nearly 40 % of its average demand. Even the change in operating level to the lowest level of the active volume i.e. to 1784m asl has very little improving in increasing the safe yield. In such case the safe yield will increase to 57m^3/s and the proportion of the corresponding hydropower supply will be 37m^3/s.

6.3.3. Assessing reliabilities of Lake Tana Supply capacity and its Navigability in various alternative development scenarios

Lake Tana sub basin is endowed with ample natural resources with suitable geophysical and agro-ecological conditions for making various socioeconomic developments. In recognition to this, the Federal Democratic Republic government of Ethiopia has identified the sub basin as one of the best areas, which have enormous potentials and contributions, for boosting the national economic development. The most fascinating natural endowment of Lake Tana natural resources are the availability of significant amount of easily exploitable water for both irrigation and hydropower developments. There is more than 100, 000ha (hectares) of land suitable for irrigation developments and there is also significant amount of water that can meet most if not all of the irrigation demands. Besides, the existence of the largest freshwater Lake, Lake Tana, is another nature's special gift to the sub basin. The Lake is used as storage for balancing the supply and demand and at the same time used for various socio economic activities like fishery developments, transportation, and recreation. Despite the enormous endowments the water resources systems planning and management practices in Lake Tana sub basin are not yet recognised well and reached its maturity level. There are many unclear and disputable ideas pertaining to the planning and managements of Lake Tana sub basin water resources systems. To mention few of them the interaction of the Lake with the surrounding aquifer is not known, and the effects of upstream irrigation developments on Lake Tana characteristics and its performance measuring indices are not also known. In such situation there is a fear that unknowingly the Lake might be harmed because of some miss management practices. And hence the overall outcome of the development endeavour may end up with some undesirable effects. It is the right time to pull and call upon all development stakeholders in the sub basin to evaluate the benefits and consequences of all possible development scenarios. One of the possible options in assessing the feasibility of various possible development scenarios is through examination of Lake Tana performance measuring indices. For this purpose, analysing the storage-reliability-yield (S-R-Y) relationship is very important.

Water supply system performance measures are receiving considerably increased attention. The performance measures of reliability, resilience, and vulnerability have been defined and introduced by a number of previous investigators. Reliability provides a measure of how often a system fails. Resilience provides a measure of how long failures will last, and vulnerability provides a measure of how severe failures may become. In other word reliability measures the frequency of failures. Resilience measures the ability of a system to recover from a failure, and vulnerability provides a measure of the magnitude of potential failures. A failure is defined as the inability of a reservoir system to deliver a pre-specified yield or service. Almost all previous investigations on Lake Tana focus on estimation of the water balance terms. There is no any study that tries to assess the performance indices of Lake Tana. This study attempts to assess the performance indices of Lake Tana specially its reliability in view of the existing and future alternative development scenarios.

The most pressing thing in assessing the performance measuring indices of Lake Tana in particular and the sub basin in general relays more on considering thoroughly the extent of upstream irrigation developments and direct withdrawal of water from the Lake. In the absence of adequate data pertinent to such kinds of studies the investigation can be carried out indirectly from the net supply perspective. The author has mentioned in chapter two that nearly 800 million cubic meters (Mm^3) of water is need as a net irrigation water requirement for all planned irrigation projects in the sub basin. This is approximately 22% of the annual net supply capacity of the sub basin. If all the anticipated irrigation projects are implemented there will be at least 22% reduction in the annual volume of the outflow from the sub basin measured at the outlet of the Lake. The net irrigation water requirement taken from the sub basin for irrigation development has no ways for it to return back to the sub basin. It is a consumptive use which will be lost from the systems in the form of evaporation and evapotranspiration.

A direct linear reduction, by an equal amount of water used for irrigation, on the net supply volume of the sub basin can be applied to examine the response of the Lake in different input environment. Such linearization in irrigation net water requirement and the reduction in the Outflow from the sub basin can be used as a strategy for designing different development scenarios. For this purpose different sizes of anticipated irrigation development options are considered and analysed. Irrigation developments that demand 10%, 15% and 20% of the sub basin net supply capacity are considered and their impacts on the performance measuring indices of the Lake are evaluated. The 10%, 15% and 20% reductions in the synthetic net supply or outflow series were applied and the reduced net supply series have been routed through the Lake. During simulation runs the reservoir is assumed full initially and then the reservoir contents are simulated with the reduced net supply series. Whenever the reservoir contents plus the net inflow/ supply in a given period are insufficient to satisfy the demand D for the hydropower and environmental flow at that period, a failure is documented. For each reduced synthetic series the performance indices of the Lake has been evaluated and recorded. Table 6.1 shows simulation results of these scenarios.

Table 6.1 Hydropower and Navigation reliabilities at different supply reduction levels

% reduction in net Supply	Navigation Reliability (%)	Hydropower reliability (%)
No reduction	95	95
10	94	89
15	92	86
20	89	82

The performance measuring indices of the Lake can also be evaluated by making a certain level of curtailment in demand for hydropower supply. It may be important to use the upstream irrigation development demands as reference for making a decision on the amount of curtailment that needs to be applied. In view of this different amount of curtailments which are equivalent to the amounts used for irrigation purpose are considered and applied. The revised hydropower demands will then be reduced by 10%, 15%, and 20%. Here it is simply make a trade off between the demand for the anticipated irrigation developments and the demand for hydropower supply. Such readjustment is presumed to maintain the performance measuring indices of the Lake for transportation service in its original condition by shifting the hydropower demand to Irrigation development. In such condition the upstream irrigation development will affect only the hydropower supply. Various scenarios arising from a combination of the reduced net inflow series and reduced demand can be considered and investigated further to examine their corresponding effect on the performance measuring indices of the Lake. This arrangement will provide us an opportunity to see the situation at a very wider range of possibilities. Here the concern is to assess the response of the system specially the Lake in various development options.

The combinations of three reduced net supplies series and other three reduced demands series will create nine different scenarios to be on board for further considerations. The same simulation procedure and operating rules, which were used in the previous cases, were also applied here to assess the effect of these scenarios on the performance measuring indices of Lake Tana. The result is presented in Tables 6.2 and 6.3 below. As it can be seen from the table when ever water is used for irrigation there should be a need to curtail the supply for the hydropower by an equal amount to maintain the reliabilities in their original values. So it is a matter of deciding to use a unit volume of water for either hydropower production or irrigation development. From economic consideration hydropower is much more attractive than irrigation. But from other perspectives it may be desirable to allow a certain level of irrigation development at the expense of power. Irrigation developments that entail a net water requirement up to 10% of the hydropower demand may be reasonable acceptable. However, attempting to develop irrigation that demands more than 10% of the hydropower demand needs serious considerations and critical investigation. One important thing that should be noted here is that the water withdrawn from the Lake for hydropower production is not used only for power production. It is also used for irrigation purposes in Beles basin. So reducing the hydropower supply because of irrigation developments in the upstream areas has an effect in both power production and irrigation development in Beles basin. A unit volume of water used for irrigation in Tana sub basin can be used to generate power and also for irrigation in Beles basin. Despite net irrigation water requirement differences in the two basin water used for generating power and then use it again for irrigation purpose is the best option that is hardly possible to deny.

Table 6.2 Hydropower reliabilities (%) at different supply and demand combinations

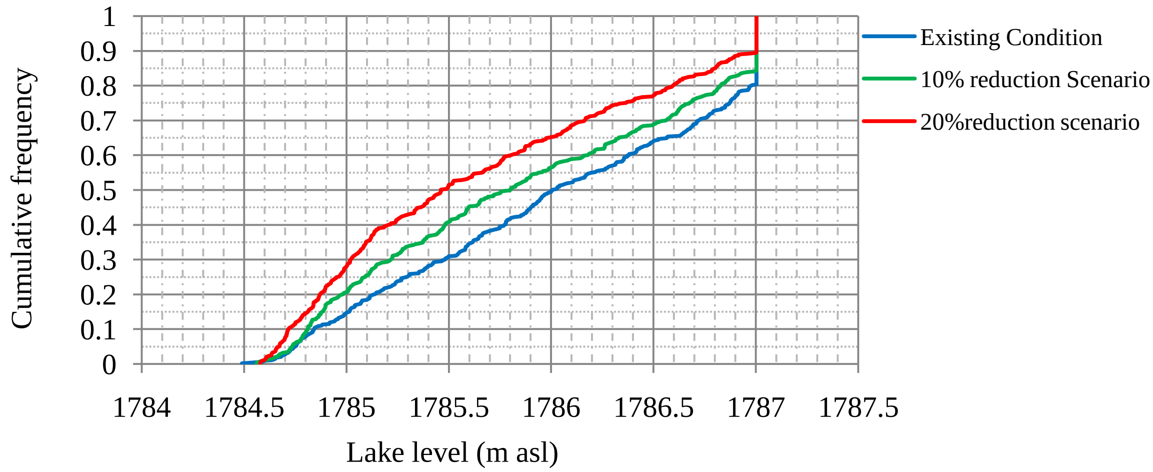
		Percent of reduced net supply to Original net supply capacity			
		100	90	85	80
Percent of reduced hydropower demand to original demand	100	95	89	86	82
	90		97	95	93
	85			97	95
	80				97

Table 6.3 Navigation reliabilities (%) at different supply and demand combinations

		Percent of reduced net supply to Original net supply capacity			
		100	90	85	80
Percent of reduced hydropower demand to original demand	100	95	94	92	89
	90		97	94	93
	85			96	96
	80				97

As far as the minimum operating level indicated above is maintained effect of irrigation development on transportation is less as compared to the effect imparted on hydropower supply in same development scenario. The effect of upstream irrigation development on Lake Tana can also be reflected on reduction occurred on its Lake Level. The reduction in Lake Level arisen from upstream irrigation developments have been assessed for all considered scenarios. For the purpose of visual examination and easy understanding, cumulative frequency plots of Lake Levels are produced and shown in Figure 6.10 for the existing condition the,10%,and 20% net supply reduction scenarios with no curtailment on hydropower demand.

Figure 6.10 Cumulative frequency plots of Lake Tana water Level for different development scenarios



Very significant reduction on the average lake Level in the order of 50cm is observed in a scenario that envisages the realization of all planned irrigation developments and no curtailment in hydropower demand. This is the most undesirable situation for both hydropower and navigation purposes and it might have also an effect on the surrounding wetlands.

6.3.4. Developing operating rule for Lake Tana

Operating rules for water resource systems must be established to specify how water is managed throughout the system. These rules are specified to achieve system stream flow requirements and system demands in a manner that maximizes study objectives. Operating rules, often established on a monthly basis, prescribe how water is to be regulated during the subsequent month based upon the current state of the system. Operation rules are often defined to include target system states, such as storage, above which one course of action is implemented and below which another course is taken. It is essential that operation rules be formulated with information that will be available at the time when operations are made.

A reservoir operation policy specifies the amount of water to be released from storage at any time depending on the state of the reservoir, level of demands and any information about the likely inflow to the reservoir. The operation problem for a single-purpose reservoir is to decide the release to be made from the reservoir so that the benefits for that purpose are maximized. For a multipurpose reservoir, additionally, it is also required to optimally allocate the release among purposes. A reservoir is operated according to a set of rules or guidelines to store and release water depending on the purposes it is required to serve. Among the most useful devices in the operation of reservoir projects is the rule curve. A rule curve is a guideline for reservoir operation, and is generally based on a detail sequential analysis of various critical combinations of hydrological conditions and demands. A rule curve or rule levels specifies the desired storage to be maintained in a reservoir as closely as possible during different times of the year while trying to meet various demands. Rule curves are generally derived by operation studies using historic or generated flows. Here the implicit assumption is that a reservoir can best satisfy its purpose if the storage levels specified by the rule curve are maintained in the reservoir at different times. A simple rule curves may base the next period's release solely on the current storage level and the current month. Because the adverse consequences of shortages are predominately those that occur during the single most severe drought of operation, a reverse routing procedure can be employed during the most critical period of record to derive an initial estimate of the rule curve. Basically three types of rule curves named as lower rule curve, upper rule curve, and operating regime are developed and used in operating a reservoir.

The Lower Rule Curve (LRC) is the trajectory of reservoir elevations during the year that defines the following:

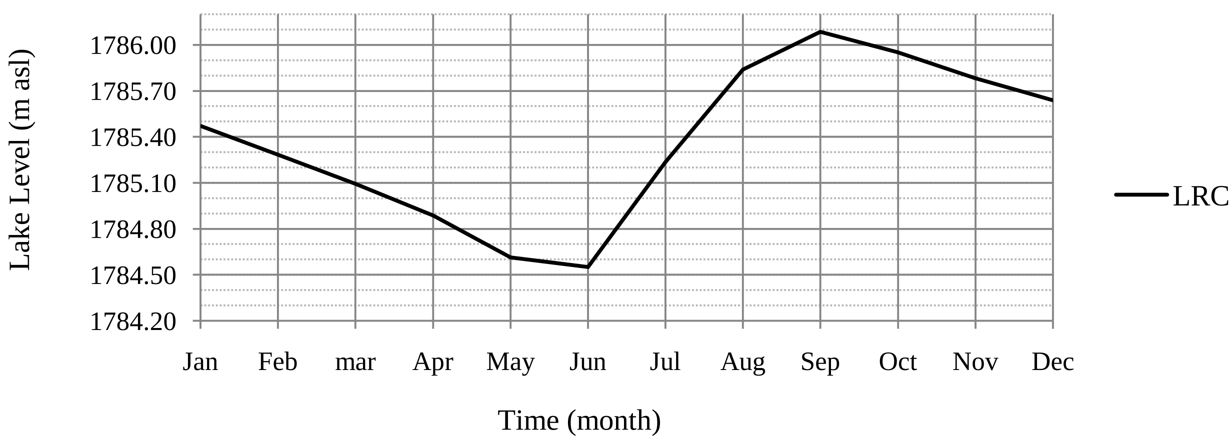
- ✓ The Maximum Firm Flow. This is the flow that can be maintained through the dry season under the lowest hydrologic condition so that the reservoir reaches its minimum operating level exactly by the end of the dry season and can be filled up to its maximum operating level during the wet season.
- ✓ The Minimum Reservoir Elevations. These are the minimum elevations that the reservoir should maintain in order to guarantee the above.

The Upper Rule Curve (URC) is the trajectory of reservoir elevations during the year that defines the following:

- ✓ The minimum spill. This is the volume that, on average will not be captured for power production as it will exceed the regulating capacity of the reservoir combined with the discharge capacity of the power plant.
- ✓ The maximum reservoir elevations. These are the maximum elevations that the reservoir should maintain in order to guarantee the above.

In fact operating Lake Tana based on its water Level is very challenging because of its very narrow operating range. The lake has very large surface area to active volume ratio. A small error in Lake Level has a significant consequence in altering the expected results. Nevertheless a Lower Rule Curve (LRC) shown in Figure 6.11is developed based on the above criteria. In developing the LRC first the critical period, the longest period from full condition through emptiness to full condition again, is selected and then the minimum elevations that the reservoir should maintain while providing the maximum possible firm yield are identified by simulating the reservoir. Hence, for each month in the critical period the minimum level of the lake has been selected and documented to develop the LRC. However, the need for developing and applying the Upper Rule Curve (URC) for operating Lake Tana is deemed to be less important because of the possibility to safely and continuously discharging any excess flow through its multiple gates provided at the regulating weir and the artificial outlet provided for supplying water to Tana Beles hydropower.

Figure 6.11 Lower Rule curve for Lake Tana Operation



The Lower and Upper Rules Curves only define a range of elevations within which the reservoir surface must maintain at the end of each month to maintain the safe yield and the safety of the dam in all the months respectively. However, reservoir operation should also show how it will be operated in releasing the target demands in the non critical periods. In all reservoir cases managing the operation based on solely on URC and LRC may not capture the whole regulation requirements. For example, if the reservoir is allowed to get too close to the lower rule curve it is possible that in a very dry month the firm flow cannot be maintained in order to stay above the curve. Hence addition operating rules called operating regime are required in order to manage properly the entire range of the reservoir.

However, further investigations on the operation of the Lake show that in most simulations runs restrictions on the target demand in all the months are required when the Lake levels are lower than the levels specified in the LRC. This indicates that the LRC can also be used and applied in managing the operation of the lake in the other periods than the critical period. Thus, in case of Lake Tana, the LRC is sufficiently enough to manage the entire operation range. It is an important guiding tool that needs to be applied in the operation management of the Lake. However, the Lake level is a very sensitive variable that needs serious operating management. Hence it has to be used in conjunction with the release volume. In all the period, other than the periods in which the reservoir is full and allowed to spill, the release volume should not exceed the target demand.

7. Summary, Conclusions and Recommendations

Lake Tana is one of nature's special gifts to Ethiopia with unique and diversified socioeconomic benefits. Its sub basin is endowed with land and water resources that can provide multiple regional and national socioeconomic benefits. In realizing this, the government of EFDR has identified the sub basin as one of the first prior areas for agricultural and industrial investments. However, the water resources systems planning and management practices in the sub basin lacks the application of appropriate models and tools. One of the basic hurdles in applying some of the existing generic water resources systems models, with some sort of modification and calibration, is the limitation of data in the sub basin. Though the sub basin is endowed with very good land and water resources its sustainable developments requires the development and careful application of appropriate tools which have the capability and provisions to incorporate most of the social, economical and ecological elements of the systems.

In this research an attempt has been made to develop a clear and applicable conceptualization with due consideration of the limitation in data for the application of other generic models. The idea of net inflow and equivalent catchment concepts have been initiated and considered to simplify the complexity associated with the hydrological processes in the Lake which eventually minimizes the uncertainties resulted from them. The idea of representing the whole area of the sub basin including the Lake area by an equivalent hypothetical catchment reduces the complexity in adequately dealing the hydrology of the Lake. Besides it helps in using the available data effectively and enables any one to understand the situation from simple catchment perspective. Hence, the outflow from the Lake or the net supply capacity of the sub basin, which is the equivalent inflow series for the hypothetical catchment, can be used in a simple straight forward manner so that it can be easily understood, manipulated and interpreted. The concept is very simplified alternative for understanding the hydrology and evaluating the water resources systems in the sub basin or its equivalent hypothetical catchment. Such conceptualization is very helpful in applying the classical reservoir design and analysis techniques and has never been applied before in the sub basin. Following the conceptualization process an attempt has been made to select appropriate data analysis and modeling techniques which fit the conceptualization and be help full in planning and management of the sub basin water resources systems. The application of stochastic modeling and simulation techniques are deemed to be very appropriate and can be easily and confidently applied to analyze the water resources systems in the sub basin.

The primarily focus in water resource systems planning and managing in the sub basin is related to the analysis of storage related problems. Getting sufficient in depth knowledge on proper analysis of storage related problems in the sub basin will give an insight to understand the overall situation from catchment perspectives. Hence storage related problems have been investigated by redesigning the required storage and making subsequent analysis for any other required issues. The classical sequent peak algorithm has been applied to determine the amount of storage required in balancing the mismatch in supply and demand. Without struggling with the hurdles in estimating all the water balance terms of the Lake it has been possible to determine easily the required active volume and place it properly in the Lake. As a result it has been ascertained the need of an active storage volume of 4.73BM^3 which can be placed by changing simply part of the dead volume of the Lake into an equivalent active volume.

To further assess the performance measuring indices of the Lake and make an investigation on the feasibility of other developments it has been important first to generate synthetic data for the net supply series. The purpose of synthetic generation of net supply series is to avoid the limitation in using the historical observed data. Applying the stochastic modeling and analysis techniques enable us to identify first order autoregressive model and a normal distribution to adequately fit the net supply series. The modeling process can lead to consider other many possible realizations and gives a better understanding which eventually can result in improved decisions being made. Following the modeling of the net supply series simulation procedures have been designed and the Lake has been simulated several times in accordance with the designed simulation procedure. The purpose of running several simulations is to determine the feasible or reasonable acceptable minimum operating Level of the Lake and to assess its performance measuring indices in view of various alternative development scenarios.

The procedures used in determining the minimum feasible operating Level of the Lake, which is based on plots of reliabilities versus Lake Level of hydropower and navigation services on same axis, is a simple unique approach which has never been applied before in other similar cases. In addition to the equivalent catchment conceptualization the procedure followed to assess the minimum feasible operating level of the Lake is a new approach that can be applied in other cases as an alternative method. Simulating the Lake using synthetic generated net supply series of different realizations with different minimum operating levels reveal that the Lake can offer equal services for both Tana Beles hydropower supply and navigation service if it is operated at a minimum operating Level of 1784.55m asl. Though the indicated operating level is not an optimum minimum operating Level it can be used as a reference guideline to evaluate any other alternative decisions. Reducing the minimum operating level of the Lake below 1784.55m asl has no any significant benefit in increasing the supply capacity of the Lake to Tana Beles hydropower plant.

The stochastic modeling and simulation processes in conjunction with the newly determined operating level have been further applied to assess the reliabilities of hydropower supply and navigation purposes at different alternative upstream irrigation development scenarios. In order to examine effect of upstream irrigation developments on reliabilities of Lake Tana in supplying Tana Beles hydropower and in navigation the total amount of net water irrigation requirement has been deducted from the original net supply series of the sub basis. The basis for making such linear reduction is that based on the fact that the net irrigation water requirement once consumed in the upstream irrigation developments has no chance to come back to the sub basin. It will be lost in the form of evaporation and transpiration. After making a revision on the net supply series by reducing the net amount of water used in the upstream irrigation projects similar simulation procedures have been used to assess the feasibility of upstream irrigation development plans and their effect on the performance measuring indices of the Lake. The approach reveals that upstream irrigation developments that demand a total net water requirement equivalent to 10% of the net supply have no significant effect on the characteristic of the Lake and the reliabilities of its services. An attempt to increase upstream irrigation net water requirement beyond 10% of the net supply capacity will have a serious harm in the reliabilities of the Lake services and its characteristics. For example, a 15% reduction in net supply will reduce the hydropower supply reliability from nearly 95% to 86% and the average level will reduce from 1786m asl to 1785.56m asl. This is believed to have a significant impact on affecting the sizes of the surrounding weight lands which by itself have an effect on water quality of the Lake and fish breeding.

Another important thing that has been dealt is the development of an operation rules for Lake Tana. Because of high surface area to active volume ratio of the Lake, operating the Lake and developing its rule curve based on entirely on its level is very challenging and sensitive that may bring undesirable changes. A 10mm Lake Level change is associated to nearly $30Mm^3$ of flow which is equivalent to the average outflow for the month of May. However, a lower rule curve has been developed which can be used as a general guiding tool in conjunction with the target release volume.

Water resources systems modeling is very complex task that requires consideration of both the physical and social environments which are known with possessing an inherent natural variability in their characteristics. To improve the planning and management of Lake Tana sub basin water resources systems the authors urge the need of an urgent special emphasis in improving the limitation in collecting and organizing sufficient and reliable information in both the physical and social environments. As the sub basin is identified as key area in providing multiple services to improve local, regional and national welfare there is no doubt that it will enter in a continuous state of stress if not managed based on strong, reliable and modern scientific tools. Hence, we strongly recommend the importance of the following points:

- Even if the sub basin is endowed with very good potentials that give various regional and national socio-economic developments opportunities it should be clearly and primarily recognized that the resources are finite and hence must be developed within the limit. An attempt to develop the resources beyond the limit may have an irreversible severe consequence. As far as possible all development endeavors should be exerted with the perspective goal of maintaining the natural characteristics and integrity of Lake Tana. To this end an attempt is need to thoroughly understand the hydrology and develop a sustainable water allocation mechanism. Implementing appropriate robotic water resources systems planning and management tools are very crucial for the sustainable development of the sub basin’s water resources systems.

- It is important and highly desirable to put more energy and resources and acclimate to continuously improve the physical, social, and economic data base pertinent to the development of the sub basin’s water resources systems planning and management models/tools. Improving the quantity and quality of both hydrological and meteorological stations and the associated data collection and acquisition techniques have very high significance in the overall water management endeavor in the sub basin and hence needs to be given special attention and priority. Because of the diversion of water from the Lake to Tana Belse Hydropower station, the measurements taken from one of the most key hydrological station found in the natural out flowing river just at the downstream of the Lake Outlet does not represent the whole Outflow from the Lake. Thus, mechanisms that synchronize the diverted flow from the Lake with the flow released in the natural river needs to be developed.
- So far there is no any effort made in collecting and disseminating data that can be used for investigating the interactions of the Lake with the surrounding groundwater. This should not continue in future. The interactions have to be investigated based on data collected from observation wells drilled in area where there are expectations for potentials of groundwater and lake interactions particularly in the southern, northeastern and eastern shorelines of the lake. Even further wells which will be used in investigating the extent of groundwater basins or aquifers in the sub basin are also very important to fully understand the hydrology of the sub basin and know the surface and sub surface areas that contribute flow to the sub basin. These will give viable information to clearly conceptualization the hydrological processes and develop appropriate models.
- Identifying the priority areas in the sub basin and developing proper water allocation and regulation mechanisms in accordance with the identified priorities and their periodic update in light of new information and knowledge are also very crucial and hence needs to be enforced very quickly.

- Strengthening the capacity and networking of institutions working at various levels such as basin, region, and national in general and the sub basin authority in particular is very indispensable to assure sustainability development.
- So far it is hardly possible to get adequate and up to date information on water quality aspects in the sub basin and the Lake. It seems that less emphasis is given to it. Enhancing this by creating an appropriate setup to monitor at least the Lake water quality is very desirable. Because of high inflow of sediment to the Lake through mainly the inflowing rivers and because of the anticipated continuous intensive agriculture practice in the sub basin special emphasis and priorities needs to be given for monitoring of suspended solids and nutrients and applying appropriate regulations systems.
- Watersheds, by nature, are dynamic systems; therefore, they are in a constant state of change associated with human activities and natural phenomenon. The inherent dynamic nature of the watersheds coupled with climate change may bring a change in the data set that will be observed in the years to come. While many changes are not detectable over short periods it is important to consider effects of the inevitable changes on the hydrological processes and impacts of climate change on the overall water resources systems planning and management in the sub basin. It is also anticipated that climate change will affects the function and operation of existing water infrastructure as well as water management practices. Hence Current water management practices in the sub basin are very likely to be inadequate to reduce the negative impacts of climate change on water-supply reliability, flood risk, energy and aquatic ecosystems. Thus it is highly advisable to incorporate impacts of climate change into the sub basin´s water related management so as to make easier adaptation to future climate changes.

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Theses

Lake Tana is one of the largest natural fresh water bodies in Ethiopia. The Lake and its sub basin have enormous potentials suitable for various socio-economic developments. Realizing its socioeconomic significance the government of Ethiopia has prepared many development plans and the implementations of some of these plans are already started since 2006. The focus of this research is, therefore, to develop applicable models that can have significant assistance to the sub basin water resources systems planning and management tasks. Thus attempts have been made to understand the problems and make a clear conceptualization that led to the development of applicable models pertaining to the planning and management of Lake Tana sub basin water resources systems. For the sake of general understanding and knowhow summary of the major assumptions, methodologies, the models developed and applied and the simulation procedures and associated results are pointed out here as follows:

1) Because of the limitation in getting all the required hydro-meteorological data in the sub basin and to circumvent the uncertainties arising from the use of various estimations methods for quantifying the unknown hydro-meteorological variables it is presumed that conceptualizing the problem in view of the available reliable hydrological records in the sub basin i.e. the Lake Level and Lake Outflow is preferable. Hence the modeling and subsequent simulation analyses effort have been designed based on the net inflow, which is computed from the water balance equation of the Lake , and the net supply (the outflow from the sub basin). The conceptualization is very simple to understand and the applications of associated models and simulation analyses are also very simple and straight forward.
2) The assumption of equivalent catchment concept is used to clarify in a simple and conventional manner the application of net supply in the planning and management of the water resources systems in the sub basin.
3) The performance measure indices of the Lake such as its reliability are taken as key criteria to assess the feasibility of overall development plans in the sub basin.
4) To avoid the limitation in using only the historical observed and recorded flows the application of stochastic modeling is believed to be highly important and hence applied to generate synthetic net supply series.
5) A first order autoregressive model and normal distributions are found to be adequate enough to represent the deseasonalized and standardized net supply series. The existence of the Lake just at the outlet of the sub basin is a good physical justification for the existence of strong autocorrelation of the net supply series and can be used as an examplenary evidence for the

application of stochastic analysis in hydrology design and analysis especially in reservoir design and operation studies.

6) The regulation made at the outlet of the Lake has changed significantly the operating range from its natural range of 2.18m to 3.38m and storage characteristics of the Lake from with-in-year to over-year storage type. The application of equivalent catchment concept coupled with the classical storage analysis methods like the sequent peak technique have easily revealed and confirmed the needs and importance of these changes. The application shows the need of additional $4.7Bm^3$ of active storage, which can be created only by changing part of the Lake dead storage into an equivalent active volume. Indeed such provision has changed the operating range and characteristics of the Lake.
7) Among the various purposes of Lake Tana, supplying water to Tana Beles Hydropower plant and Navigation are the most important but conflicting purposes. A very simple technique has been developed to determine a reasonably acceptable minimum operating Level of the Lake that can treat both services equally. The technique involves plotting of reliabilities versus minimum operating levels of the Lake for both the hydropower and navigation services on same axes. Application of the technique shows that the Lake can give equal services if operated at a minimum operating level of 1784.55m asl. It is a unique approach that has never been applied before in the lake and elsewhere.
8) It is obvious that the development of irrigations in the upstream areas of the sub basin will reduce the net supply capacity of the sub basin and consequently the performance of the Lake in supplying Tana Beles and its navigability will be affected. The extent of such effects have been assessed and ascertained that more than 10% reduction in the net supply capacity of the Sub basin because of upstream irrigation development have significant impact on Tana Beles supply and navigation reliabilities.
9) The development and applications of rule curves for reservoir operation are important tools that have been used most often in many reservoirs. A lower rule curve which can be used as a general guiding tool in the operation management of Lake Tana is developed.
10) Developing and implementing appropriate robotic water resources systems planning and management tools are still very crucial for the sustainable development of the sub basin's water resources systems.

Appendix A: Figures

Figure A1. Hydrograph of Lake Tana Outflow and water level

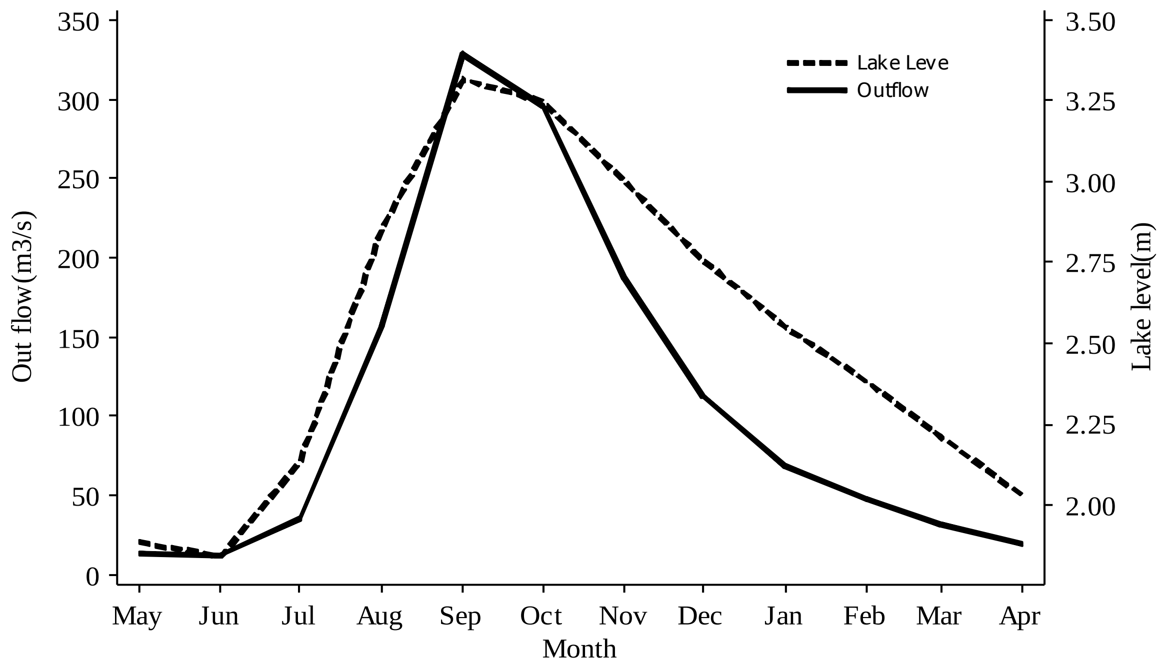


Figure A2 Time Series Plot of Naturalized and Obesrved Lake level

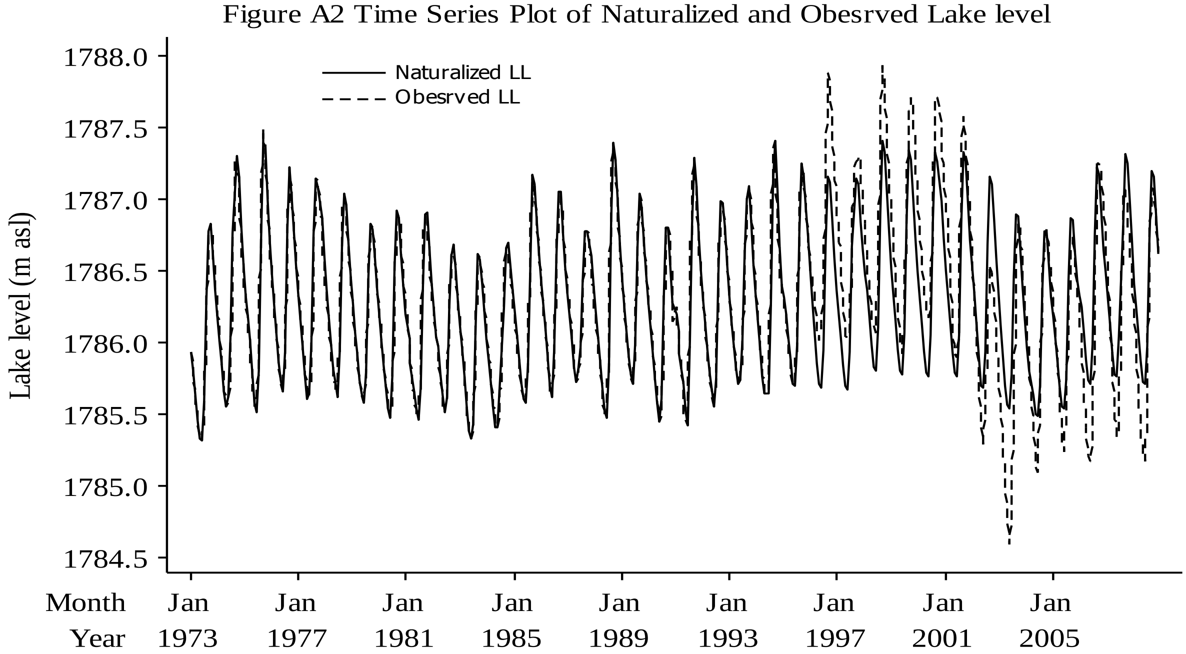


Figure A3 Time Series Plot of Naturalized and Observed Outflow

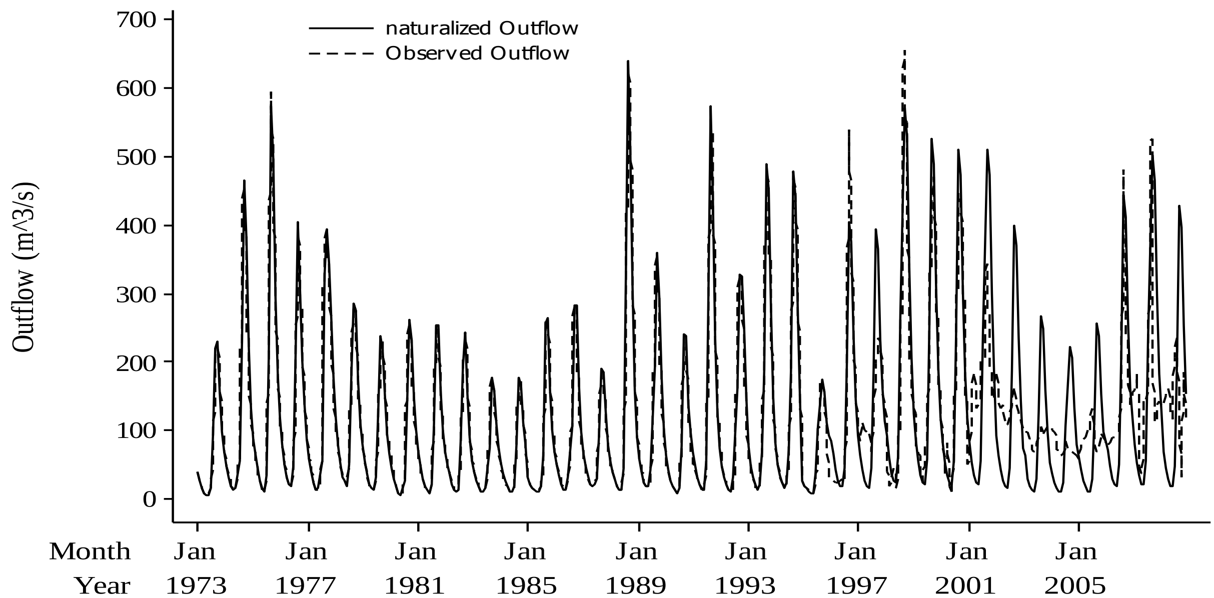


Figure A4 Chart of three years average Annual Net Inflow

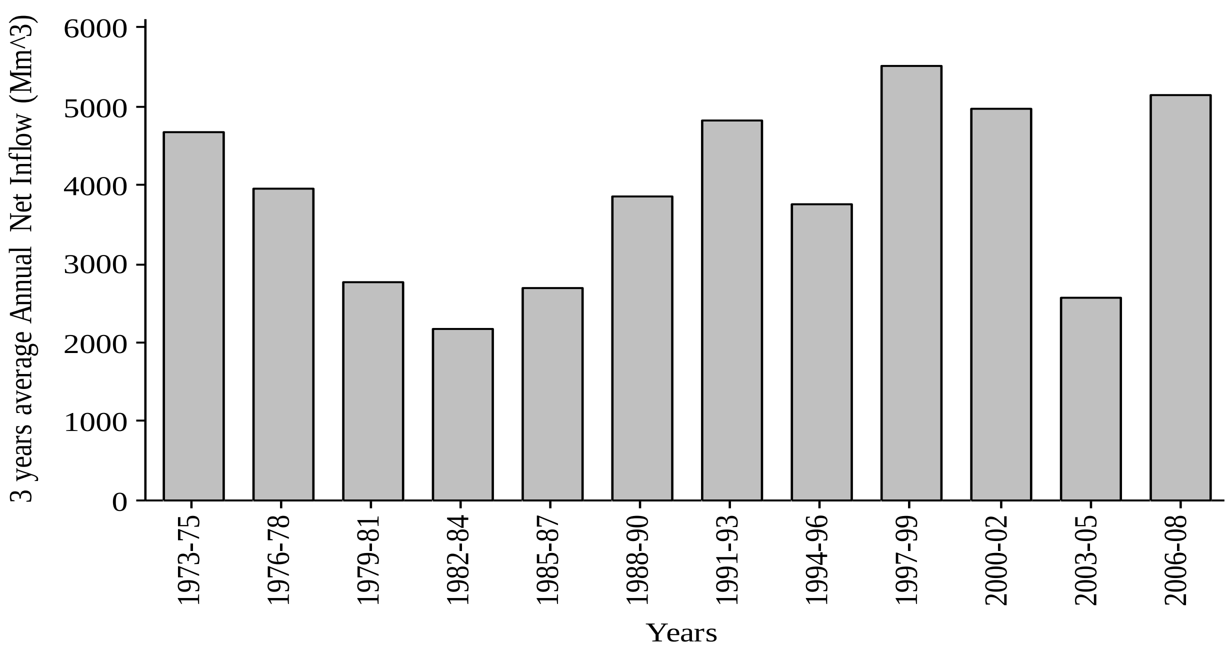


Figure A5 Chart of Monthly Net inflow Starting from Jan,1973 to Dec, 1990

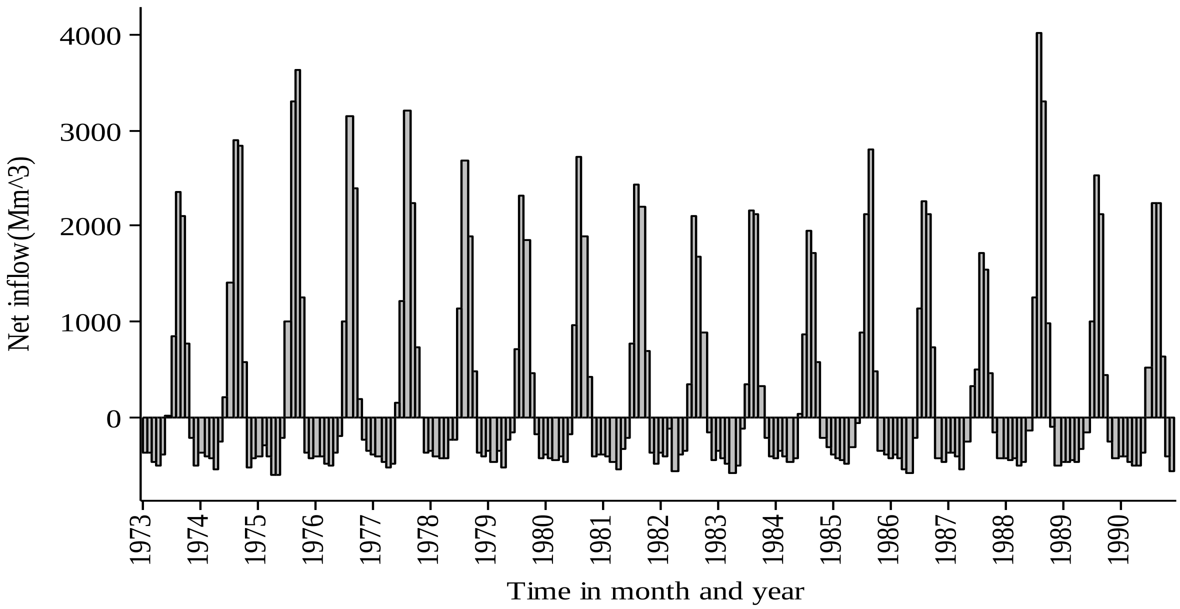


Figure A6 Chart of Monthly Net Inflow Starting from Jan, 1991 to Dec, 2008

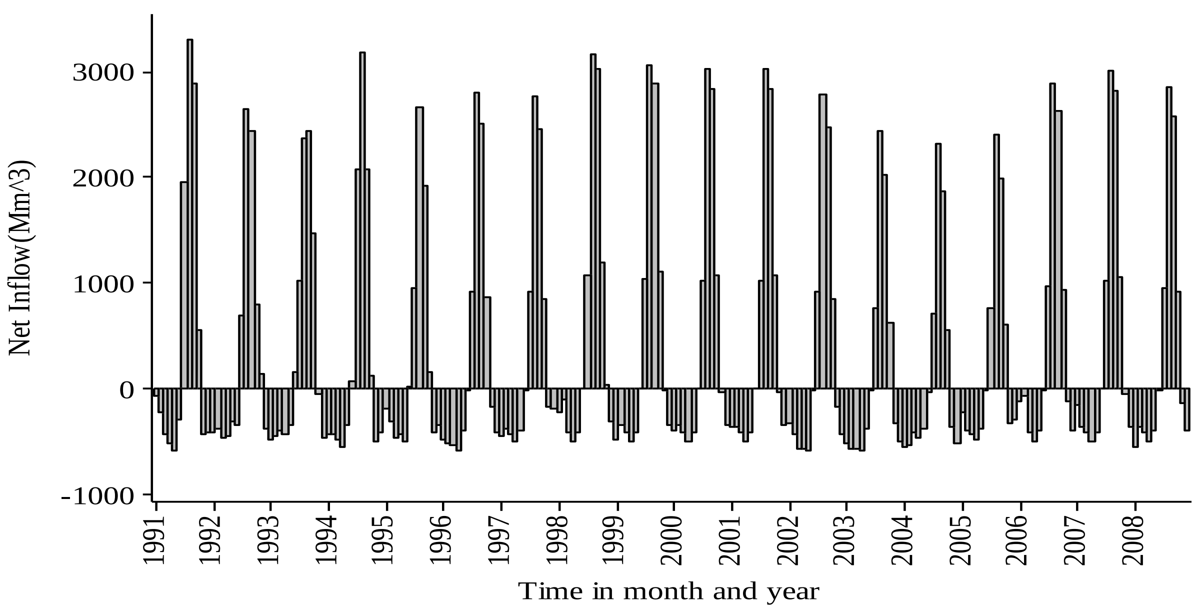


Figure A7 Time Series Plot of monthly net supply volume

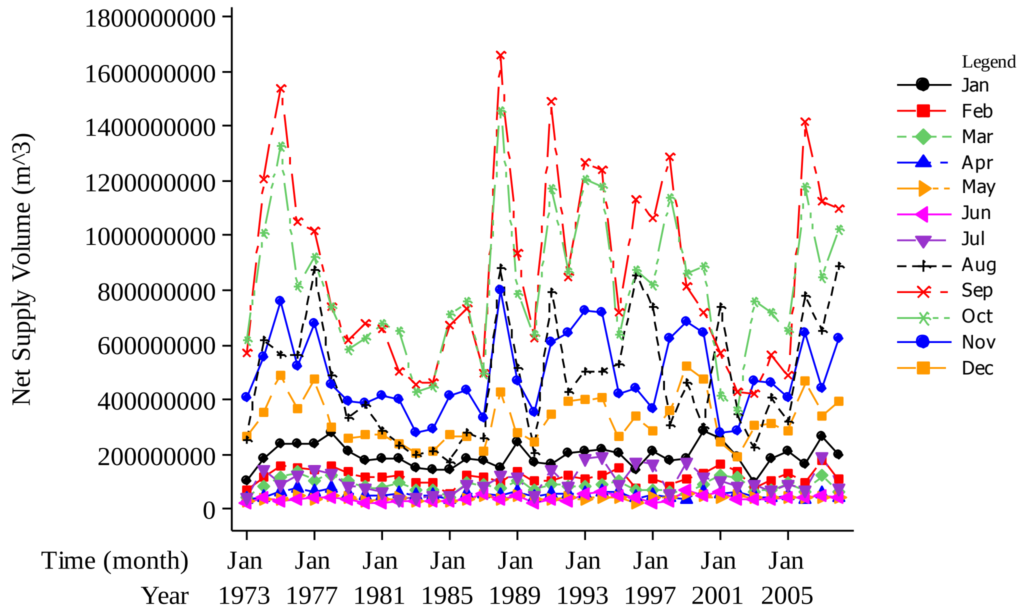


Figure A8 ACF of Residuals for standardized net supply series
(with 5% significance limits for the autocorrelations)

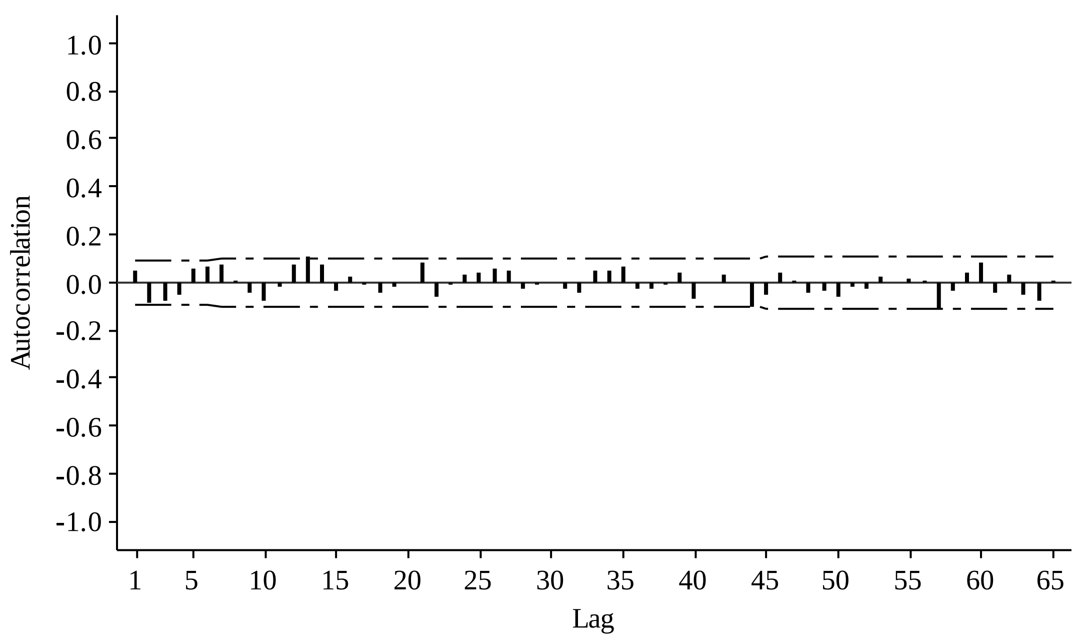


Figure A9 PACF of Residuals for the standardized net supply series
(with 5% significance limits for the partial autocorrelations)

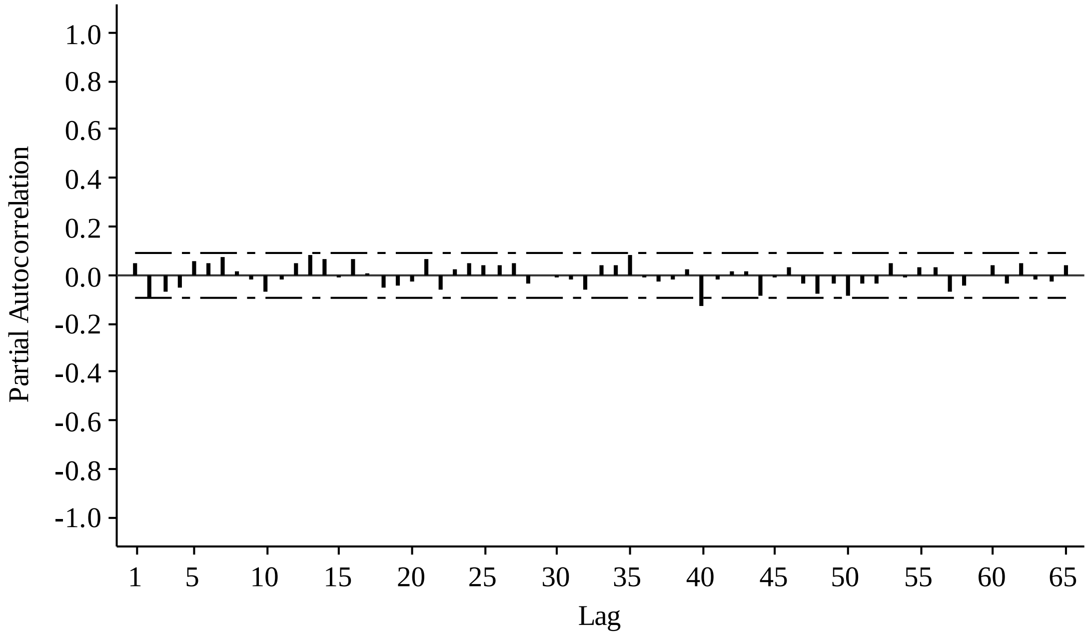
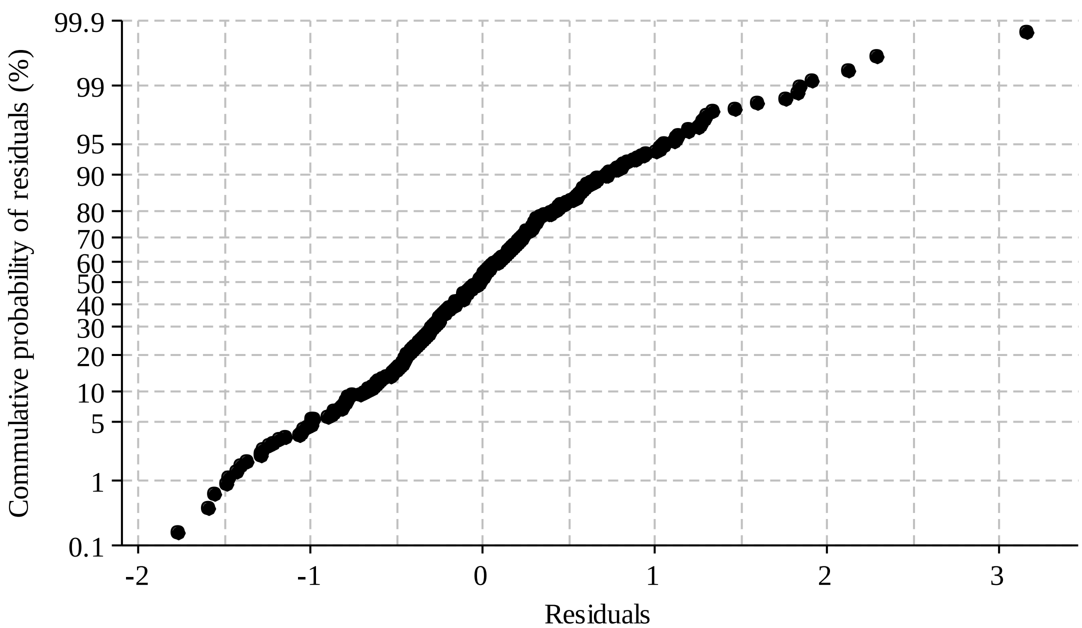


Figure A10 Probability Plot of Residual for the standardized net supply series
Normal



Appendix B: Tables

Table B1. Comparison of results of different studies on Lake Tana Water balance estimate

Water Balance terms	**Studies**							
	Kebede et al.		SMEC		Chebud		Wale	
	mm	MCM	mm	MCM	mm	MCM	mm	MCM
Precipitation	1451	4579	1264	3816	1200	3780	1220	3784
Evaporation	1478	4664	1675	5073	1460	4600	1690	5242
Inflow	1162	3667	1646	4986	1352	4260	2160	6699
Out flow	1113	3512	1243	3753	1108	3500	1520	4717

Table B2 Some Features of Ethiopia's drainage basins (source: MOWR, 2002)

No.	River basin	Catchment area (km^2)	Annual runoff (Bm^3)	Specific discharge ($l/s/km^2$)	Potential irrigable Land (ha)	Hydroelectric Potential(Gwh/y)
1	Abbay	199 812	52.6	7.8	815,581	78,820
2	Awash	112 700	4.6	1.4	134,121	4,470
3	Baro-Akobo	74 100	23.6	9.7	1,019,523	13,765
4	Genale –Dawa	171 050	5.80	1.2	1,074,720	9,270
5	Mereb	5 700	0.26	3.2	67,560	-
6	Omo-Gibe	78 200	17.90	6.7	67,928	36,560
7	Rift Valley	52 740	5.60	3.4	139,300	800
8	Tekeze	89 000	7.63	3.2	83,368	5,980
9	Wabe Shebele	200 214	3.15	0.5	237,905	5,440
10	Afar-Danakil	74 000	0.86	-	158,776	
11	Ogaden	77 100	0	-	-	-
12	Aysha	2 200	0	-	-	-
	Total	1 136 816	122.00		3,798,782	155,102

Table B3 List of planned dams and reservoirs and their project status in Tana sub basin

River Name	Dan and Reservoir Main feature	Project Status
Megech	76m high storage dam on Megech River, 181 million m^3 reservoir	Design completed
Ribb	73m high storage dam on Ribb river, 233 million m^3 reservoir	Dam under construction to be completed soon
Gumara	33m high storage dam on Gumara River, 223 million m^3 reservoir	Studied to design level
Koga	25m high storage dam on Koga River, 77 million m^3 reservoir	Dam and irrigation infrastructure completed and commissioned
Jema	71m high storage dam on Jemma River, 173 million m^3 storage	Feasibility study completed
Gilgel Abbay	Storage dam on Gilgel abbay River, 563 million m^3 reservoir	Feasibility study completed

Table B4 Statistical characteristics of Regulated Lake Level

Month	Average (m asl)	Std.Dev (m asl)	Coefficient of variation (x 10^{-2})	Minimum (m asl)	Maximum (m asl)	Skewness
Jan	1786.5	0.376	0.02	1785.8	1787	-0.47
Feb	1786.3	0.382	0.02	1785.5	1786.9	-0.41
Mar	1786.1	0.391	0.02	1785.3	1786.6	-0.51
Apr	1785.8	0.410	0.02	1785.0	1786.4	-0.48
May	1785.6	0.438	0.02	1784.8	1786.2	-0.39
Jun	1785.6	0.491	0.03	1784.6	1786.2	-0.33
Jul	1785.9	0.476	0.03	1785.0	1786.5	-0.12
Aug	1786.7	0.504	0.03	1785.8	1787.4	-0.16
Sep	1787.2	0.49	0.03	1786.5	1787.9	-0.05
Oct	1787.2	0.425	0.02	1786.5	1787.8	0.04
Nov	1787	0.407	0.02	1786.3	1787.6	-0.23
Dec	1786.8	0.373	0.02	1786.0	1787.3	-0.46

Table B5 Statistical characteristics of unregulated Lake Level

Month	Average (m asl)	Std.Dev (m asl)	Coefficient of variation (x 10^{-2})	Minimum (m asl)	Maximum (m asl)	Skewness
Jan	1786.3	0.131	0.01	1785.9	1786.5	-0.59
Feb	1786.1	0.12	0.01	1785.8	1786.3	-0.57
Mar	1785.9	0.115	0.01	1785.6	1786.1	-0.88
Apr	1785.7	0.113	0.01	1785.5	1785.9	-0.84
May	1785.6	0.120	0.01	1785.3	1785.8	-0.68
Jun	1785.6	0.128	0.01	1785.3	1785.8	0.06
Jul	1785.8	0.191	0.01	1785.4	1786.3	-0.13
Aug	1786.6	0.261	0.01	1786.1	1787.1	0.20
Sep	1787.0	0.263	0.01	1786.6	1787.5	0.12
Oct	1787.0	0.195	0.01	1786.6	1787.4	0.15
Nov	1786.7	0.152	0.01	1786.4	1787.0	0.19
Dec	1786.5	0.132	0.01	1786.2	1786.7	0.00

Table B6 Statistical characteristics of naturalized Lake Level

Month	Average (m asl)	Std.Dev (m asl)	Coefficient of variation (x 10^{-2})	Minimum (m asl)	Maximum (m asl)	Skewness
Jan	1786.3	0.114	0.01	1786.0	1786.5	-0.18
Feb	1786.1	0.104	0.01	1785.9	1786.3	-0.21
Mar	1785.9	0.119	0.01	1785.6	1786.1	-0.59
Apr	1785.7	0.122	0.01	1785.5	1785.9	-0.70
May	1785.6	0.125	0.01	1785.3	1785.8	-0.66
Jun	1785.6	0.148	0.01	1785.3	1785.8	-0.07
Jul	1785.9	0.216	0.01	1785.4	1786.3	-0.47
Aug	1786.6	0.261	0.01	1786.1	1787.1	0.08
Sep	1787.0	0.270	0.02	1786.6	1787.5	0.06
Oct	1787.0	0.202	0.01	1786.5	1787.4	-0.18
Nov	1786.7	0.151	0.01	1786.4	1787.0	-0.04
Dec	1786.5	0.128	0.01	1786.2	1786.7	0.01

Table B7 Statistical characteristics of Regulated Outflow

Month	Average (m^3/s)	Std.Dev (m^3/s)	Coefficient of variation (x 10^{-2})	Minimum (m^3/s)	Maximum (m^3/s)	Skewness
Jan	73.58	18.06	24.55	35.78	106.18	-0.09
Feb	48.02	13.60	28.33	28.65	73.80	0.43
Mar	30.30	9.19	30.33	19.76	45.87	0.68
Apr	18.34	3.60	19.61	13.98	24.11	0.28
May	14.66	2.32	15.79	8.56	19.46	-0.76
Jun	15.96	4.80	30.05	8.86	27.24	0.97
Jul	40.15	17.16	42.74	21.29	71.83	0.81
Aug	200.20	86.20	43.06	82.20	330.0	0.19
Sep	325.7	129.7	39.81	160.7	545.4	0.23
Oct	297.1	88.2	29.68	134.0	438.7	-0.27
Nov	186.6	52.8	28.29	106.2	263.0	0.06
Dec	126.62	35.25	27.84	69.63	193.53	0.53

Table B8 Statistical characteristics of unregulated Outflow

Month	Average (m^3/s)	Std.Dev (m^3/s)	Coefficient of variation (x 10^{-2})	Minimum (m^3/s)	Maximum (m^3/s)	Skewness
Jan	70.30	15.26	21.71	38.13	102.51	0.08
Feb	47.09	10.77	22.87	21.20	65.13	-0.53
Mar	32.40	8.37	25.84	16.02	50.10	0.07
Apr	20.13	4.16	20.65	12.43	28.84	0.23
May	13.35	2.78	20.79	9.32	18.85	0.58
Jun	12.69	4.36	34.34	6.52	22.26	0.80
Jul	35.40	17.45	49.27	11.55	70.31	0.47
Aug	161.50	81.40	50.41	63.70	328.10	0.77
Sep	340.3	143.2	42.09	175.4	638.1	0.75
Oct	306.6	108.1	35.27	159.3	543.7	0.73
Nov	192.9	61.4	31.81	106.6	307.8	0.52
Dec	117.39	32.08	27.33	74.72	182.09	0.60

Table B9 Statistical characteristics of naturalized Outflow

Month	Average (m^3/s)	Std.Dev (m^3/s)	Coefficient of variation (x 10^{-2})	Minimum (m^3/s)	Maximum (m^3/s)	Skewness
Jan	71.58	16.24	22.68	35.78	106.18	0.04
Feb	47.45	11.77	24.80	21.20	73.80	0.02
Mar	31.58	8.63	27.33	16.02	50.10	0.28
Apr	19.44	3.99	20.54	12.44	28.84	0.31
May	13.86	2.65	19.13	8.56	19.46	0.09
Jun	13.96	4.75	34.01	6.52	27.24	0.79
Jul	37.25	17.25	46.30	11.55	71.83	0.54
Aug	176.5	84.3	47.74	63.7	330.0	0.51
Sep	334.6	136.4	40.76	160.7	638.1	0.59
Oct	302.9	99.6	32.89	134.0	543.7	0.50
Nov	190.45	57.48	30.18	106.18	307.82	0.41
Dec	120.98	33.17	27.41	69.63	193.53	0.56

Table B10 Statistical characteristics of net inflow

Month	Average (Mm^3)	Std.Dev (Mm^3)	Coefficient of variation (x 10^{-2})	Minimum (Mm^3)	Maximum (Mm^3)	Skewness
Jan	-416.0	110.9	-26.65	-672.0	-84.2	0.33
Feb	-406.2	142.6	-35.11	-720.4	-18.9	0.43
Mar	-442.7	138.0	-31.18	-786.2	-124.1	-0.31
Apr	-510.2	108.4	-21.25	-789.1	-192.1	0.46
May	-384.5	130.9	-34.05	-732.5	-151.4	-0.60
Jun	-57.6	328.4	-570.40	-687.8	1094.2	0.95
Jul	1042.5	530.8	50.91	303.6	2736.7	1.24
Aug	2713	829	30.55	1352	5286	1.10
Sep	2107	775	36.78	2107	4144	0.32
Oct	614.3	411.5	66.98	-178.8	1584.1	0.27
Nov	-283.7	229.2	-80.79	-729.0	283.7	0.06
Dec	-372.5	147.6	-39.63	-647.7	43.5	0.98

Table B11 Trend analysis for Outflow

Month	Value of the test statistics	Critical value of the student's t distribution	Comment
May	2.427	2.032	trend
Jun	2.780	2.032	trend
Jul	0.952	2.032	No trend
Aug	1.216	2.032	No trend
Sep	0.045	2.032	No trend
Oct	0.739	2.032	No trend
Nov	0.520	2.032	No trend
Dec	0.984	2.032	No trend
Jan	1.800	2.032	No trend
Feb	-0.480	2.032	No trend
Mar	-1.283	2.032	No trend
Apr	-1.035	2.032	No trend

Table B12 Trend analysis for net inflow

Month	Value of the test statistics	Critical value of the student's t distribution	Comment
May	1.381	2.032	No trend
Jun	1.365	2.032	No trend
Jul	-0.002	2.032	No trend
Aug	0.049	2.032	No trend
Sep	-1.733	2.032	No trend
Oct	0.394	2.032	No trend
Nov	-0.404	2.032	No trend
Dec	2.564	2.032	trend
Jan	-1.284	2.032	No trend
Feb	1.215	2.032	No trend
Mar	0.964	2.032	No trend
Apr	0.030	2.032	No trend

Table B13 Mean and variance Stability analysis for the Outflow

Months	Sub set one period of analysis	Sub set two period of analysis	v_1, v_2	$F_{2.5\%}$ F_t $F_{97.5\%}$	v	$t_{2.5\%}$ t_t $t_{97.5\%}$	Comment
Jan	1973-1990	1991-2008	17, 17	0.370 1.024 2.670	34	-2.037 -0.037 2.037	Both mean and variance are stable
Feb	1973-1990	1991-2008	17, 17	0.370 1.009 2.670	34	-2.037 -0.007 2.037	Both mean and variance are stable
Mar	1973-1990	1991-2008	17, 17	0.370 1.316 2.670	34	-2.037 0.034 2.037	Both mean and variance are stable
Apr	1973-1990	1991-2008	17, 17	0.370 1.911 2.670	34	-2.037 0.050 2.037	Both mean and variance are stable
May	1973-1990	1991-2008	17, 17	0.37 2.048 2.67	34	-2.037 -0.087 2.037	Both mean and variance are stable
Jun	1973-1990	1991-2008	17, 17	0.370 0.602 2.670	34	-2.037 -0.152 2.037	Both mean and variance are stable
Jul	1973-1990	1991-2008	17, 17	0.370 0.616 2.670	34	-2.037 -0.130 2.037	Both mean and variance are stable
Aug	1973-1990	1991-2008	17, 17	0.370 1.093 2.670	34	-2.037 -0.104 2.037	Both mean and variance are stable
Sep	1973-1990	1991-2008	17, 17	0.37 1.030 2.670	34	-2.037 -0.055 2.037	Both mean and variance are stable
Oct	1973-1990	1991-2008	17, 17	0.370 1.175 2.67	34	-2.037 -0.067 2.037	Both mean and variance are stable
Nov	1973-1990	1991-2008	17, 17	0.37 1.023 2.67	34	-2.037 -0.073 2.037	Both mean and variance are stable
Dec	1973-1990	1991-2008		0.37		-2.037	Both mean and

			17, 17	1.023 2.67	34	-0.099 2.037	variance are stable

Table B14 Hydropower Water demand and Corresponding Energy production

Months	Power demand in (m^3/s)	Environmental Flow in (m^3/s)	Total Demand in (m^3/s)	Total Demand in (*10^6 M^3)	Energy production (GWH)
Jan	77.71	20.00	97.71	261.70	176.67
Feb	65.73	20.00	85.73	207.41	122.38
Mar	71.35	20.00	91.35	244.68	148.96
Apr	65.33	20.00	85.33	221.17	134.14
May	53.18	20.00	73.18	196.00	91.68
Jun	58.67	20.00	78.67	203.92	126.72
Jul	54.13	20.00	74.13	198.55	113.35
Aug	94.30	20.00	114.30	306.13	142.52
Sep	104.44	20.00	124.44	322.55	123.13
Oct	98.91	20.00	118.91	318.48	139.85
Nov	78.01	20.00	98.01	254.03	141.83
Dec	78.15	20.00	98.15	262.89	151.64
Total				**2997.52**	**1612.87**

Table B15 Drinking water quality standards of Ethiopia (Source Dagnew et al., 2010)

Water Quality parameter	Maximum permissible limit
Turbidity, NTU	5
Colour, TCU	15
pH value	6.5 to 8.5
Total alkalinity as ($CaCO_3$), mg/l	200
Total hardness (as $CaCO_3$)mg/l	300
Total dissolved solids mg/l	1000
Total iron (as Fe) mg/l	0.3
Manganese (as Mn) mg/l	0.5
Zinc (as Zn), mg/l	5
Copper (as Cu), mg/l	2
Magnesium (as Mg), mg/l	50
Calcium (as Ca), mg/l	75
Ammonia (NH_3 +NH^+_4), mg/l	1.5
Chloride (as Cl), mg/l	250
Fluoride (as F), mg/l	1.5
Arsenic (as AS), mg/l	0.01

Lead (as Pb), mg/l	0.01
Mercury (as Hg), mg/l	0.001
Cyanides (as CN), mg/l	0.07
Nitrate as NO_3, mg/l	50
Sulfate (as SO_4), mg/l	250
Coliform organisms, number per 100ml	nil

Table 16 Elevation, Volume, and Area Characteristics of Lake Tana (Source Studio Pietrangeli: 1990)

Lake Level(m asl)	Volume(Mm^3)	Area(km^2)
1772	0	0
1773	119	238
1774	709	942
1775	1903	1445
1776	3497	1743
1777	5353	1970
1778	7425	2173
1779	9688	2354
1780	12120	2509
1781	14695	2642
1782	17401	2769
1783	20227	2883
1784	23147	2958
1785	26135	3018
1786	29175	3062
1787	32273	3134
1788	35444	3207

Appendix C: Some features of Nile basin water resources systems

Nile is one of the great rivers of the world, feeding millions and giving birth to entire civilizations. It is one of the world's longest rivers, traversing about 6,695 kilometers from the farthest source of its headwaters of the Kagera Basin in Rwanda and Burundi through Lake Victoria, to its delta in Egypt on the Mediterranean Sea. Its basin includes eleven African countries (Burundi, DR Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, The Sudan, and Tanzania). Nile Basin countries are today home to more than 437 million people and of these, 54% (238 million) live within the basin (www.nilebasin.org).

Notwithstanding the basin has natural and environmental endowments and rich cultural history, its people face considerable challenges including persistent poverty with millions living on less than a dollar a day. Despite these seemingly formidable challenges, the River Nile holds tremendous potentials and opportunities for regional and national growth which includes increased hydropower and food production and more control over damage from floods and droughts.

The basin has a surface area of 3,112,369km^2 which represents about ten percent of Africa's land mass area. The average annual flow of the Nile is estimated as 84 billion m^3, measured at Aswan High Dam. Most of the water is generated from the Ethiopian highlands which constitute less than 12% of the basin area. The flow generated in Ethiopia including the flows from Blue Nile, Tekeze and Baro akobo sub basins constitutes 86% of the total flow of Nile measured at Aswan High Dam. The average annual discharge of the Blue Nile alone, at the Ethio- Sudan boarder, is about 50 billion m^3. Figure C1 and C2 and the Tables from C1 to C4 show some features of the basin's hydrology and water resources systems.

Table C1 list of countries, their area and mean annual rainfall in the basin

Country	Total area of the country (km^2)	Area of the country with in the basin (km^2)	Mean annual rain fall in the basin (mm)
Burundi	27,834	13,260	1110
D.R Congo	2,344,860	22,143	1245
Egypt	1,001,450	326,751	15
Eritrea	121,890	24,921	520
Ethiopia	1,100,010	365,117	1125
Kenya	580,370	46,229	1260

Rwanda	26,340	19,876	1105
Sudan + South Sudan	2,505,810	1,978,506	500
Tanzania	945,090	84,200	1015
Uganda	235,880	231,366	1140
Nile basin	8,889,534	3,112,369	615

Figure C1 Map of Nile river basin

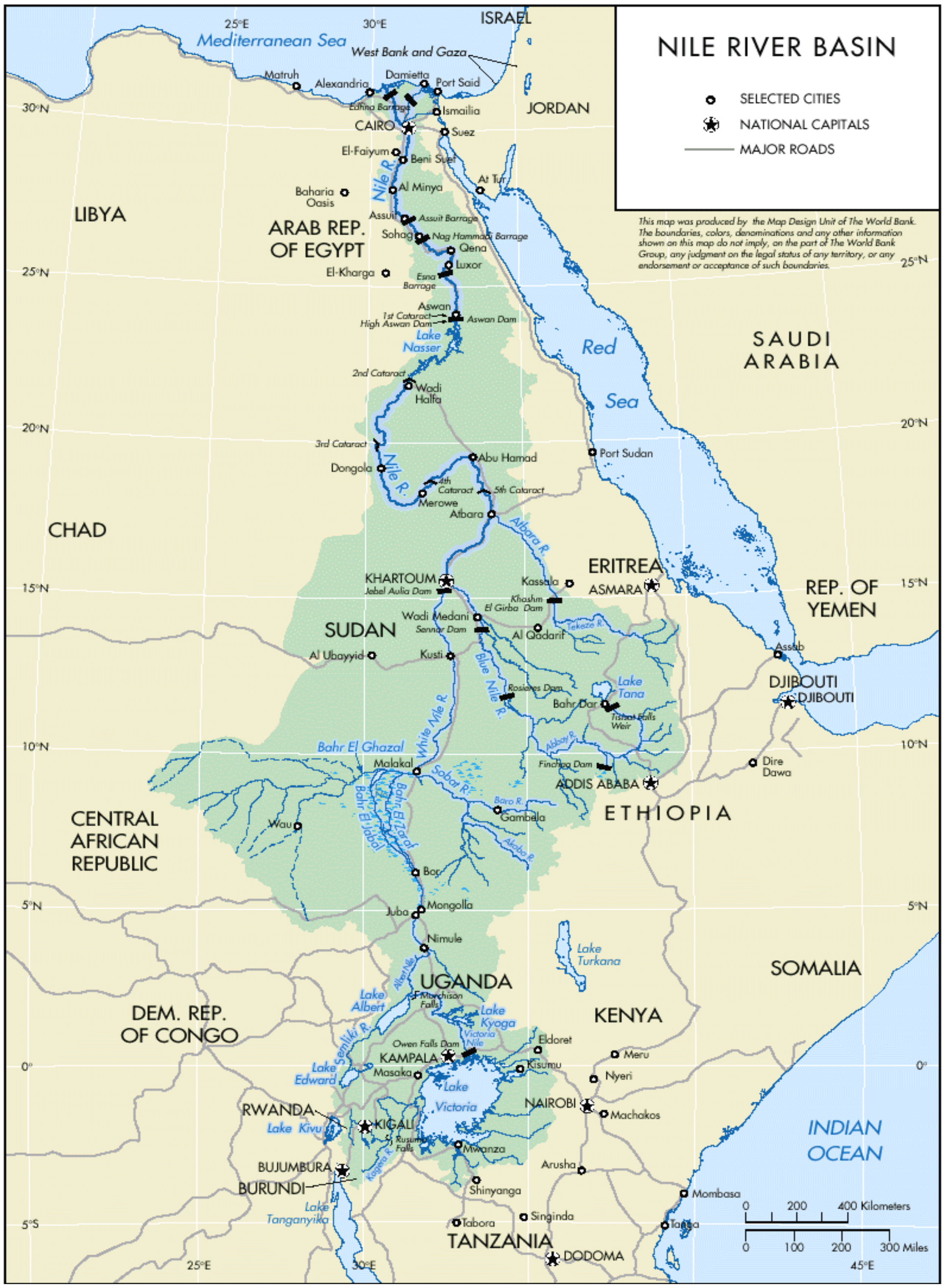


Table C2 Mean monthly flow volume (Mm^3) of Blue Nile and Main Nile at some selected stations

Month	At the outlet of Lake Tana near Bahir dar	At Ethio-sudan boarder	At Khartoum	Inflow to Aswan High Dam
Jan	191.71	924.05	636.85	1683.33
Feb	115.75	554.00	385.65	1347.47
Mar	84.59	433.90	474.50	1337.53
Apr	50.39	365.47	963.38	1944.99
May	37.12	642.82	819.02	2582.51
Jun	36.19	1871.42	1006.28	1957.48
Jul	99.77	7609.33	3630.95	5141.66
Aug	472.85	15090.11	13445.47	17853.34
Sep	867.33	11249.28	10957.25	17741.68
Oct	811.38	6610.29	4809.09	7878.36
Nov	493.65	2641.25	2061.06	4651.67
Dec	324.04	1408.84	998.27	2482.50
Annual	3584.76	49400.76	40187.77	66602.52

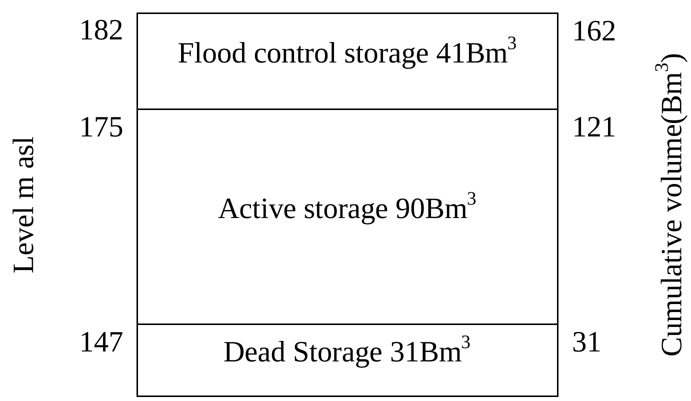
Table C3 Mean Monthly net evaporation (mm) for some reservoirs in Blue Nile and main Nile

Month	Lake Tana	Roseries	Aswan High Dam
Jan	122	180	149
Feb	141	185	141
Mar	171	227	166
Apr	140	221	171
May	76	189	214
Jun	-42	63	241
Jul	-263	-28	269
Aug	-231	-26	281
Sep	-15	20	288
Oct	77	125	269
Nov	114	157	201
Dec	118	167	177
Annual	408	1480	2568

Table C4 Features of some storage reservoirs in Blue Nile and main Nile

Dam	Total Storage Volume (Bm^3)	Active Storage Volume(Bm^3)	Surface Area (km^2)	Purpose
Lake Tana	32	9	3050	Hydropower
Grand Renaissance	74	58	1680	Hydropower
Roseires	2.02	1.99	274	Hydropower and irrigation
Sennar	0.48	0.41	152.6	Hydropower and irrigation
Merowe	12.45	8.300	800	Hydropower
Aswan High Dam	162	90	6000	Flood control, irrigation and hydropower

Figure C2 Partitions of Lake Nasser (the Multipurpose Reservoir at Aswan High Dam)



Publication list:

Journal Article:

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Conference proceedings Paper:

Belete Mulugeta Azeze; Yilma Seleshi; Hartmut Eckstädt (2012). Assessing Reliabilities of Multipurpose Reservoir Using Stochastic Modeling and Scenario Based Simulations of Net Inflow, the Case of Lake Tana, Ethiopia. In Proceedings of national conference on science, technology, and innovation for prosperity of Ethiopia. Bahir Dar: Bahir Dar University.

Book:

Belete, Muluget Azeze (2010). Synthetic Unit Hydrographs for Upper Awash and Tekeze Basins. VDM Verlag: Germany.