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Simulation and Analysis of Possible Water Balance Scenarios of Lake Bosomtwe

Environmental Resources Management Program

Department of Materials Engineering

MSc. Thesis

by

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Simulation and Analysis of

Possible Water Balance Scenarios of Lake Bosomtwe

by

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CERTIFICATION

I hereby declare that this submission is my own work towards the award of a Master of Science (MSc) in Environmental Resources Management and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

The hydrology and hydrodynamics of Lake Bosomtwe has been studied but not exhausted. Thus in this study, a model is developed using the system dynamics approach to mimic hydrological processes that take place within the lake's catchment area. The model uses rainfall data for Kumasi as input to simulate surface runoff whereas temperature, relative humidity and solar radiation data for the aforementioned is employed in simulating evaporation from the lake surface as well as evapotranspiration from the catchment land surface. Similarly population estimates for the communities within the catchment area in conjunction with the annual water demand per capita for Ghana is used in estimating water abstraction from the lake for domestic and agricultural purposes from the period of 1984 to 2013. After calibrating and validating the model, the resulting simulated lake water level from the model is compared to that which is observed. Obtaining a co-efficient of determination (R^2) value of 0.93 for the model, both land use(s)/land cover and climate scenarios are developed for the assessment of possible potential impacts on the lake's hydrodynamics. The results from the study suggest that there are two seasons (namely the rainy and dry seasons) influencing the hydrology of the lake. Rather than the absolute climatic stance as purported by earlier researchers, the lake is also affected by anthropogenic factors particularly water abstraction for domestic and agricultural activities. However the climatic component is the dominant factor responsible for the lake water dynamics. Of all the climatic components, the variability in the amount of rainfall is the major component responsible for determining the dynamic lake water level behaviour (noise) observed. Finally, whiles the magnitude of water losses is driven by both climatic and anthropogenic forces at present, it is very possible that in the near future, the lake's water level depreciation will be by far due to anthropogenic pressures as compared to the climatic.

LIST OF ACRONYMNS

CERGIS	Centre for Remote Sensing and Geographic Information Systems
EPA	Environmental Protection Agency
HBV	Hydrologiska Byråns Vattenbalansavdelning
HEC- HMS	Hydrologic Engineering Centre – Hydrological modelling system
ITCZ	Intertropical Convergence Zone
MAB	Man and Biosophere
NWSRFS	National Weather Service River Forecasting System
SHE	Systemé Hydrologiqué European

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CHAPTER 1 CONCEPTS AND CONTENTS OF MODELLING

1.1 Introduction

Models have played very significant roles in the quest to understand and manage environmental problems. By focusing on the features or components that are essential (in the context of the problem to be solved), models tend to mimic complex realities in a simplified manner. Their functional role is to construct a conceptual framework that describes a system. Thus, models can be defined as virtual constructs of real life systems that provide the opportunity for the investigation of a system's properties, and in some cases, the forecasting of future outcomes. They can be material, visual, mathematical or computational and are often used in the construction of scientific theories.

One of such commonly used models is the water balance model. The fundamental concept underlying this model is to appreciate how water systems naturally maintain themselves by identifying inflows as well as outflows and possibly their rates. According to Vining and Vecchia (2007), water balance models can provide effective means for evaluating the sensitivity of water availability or flood risk to historical and hypothetical future climate conditions. This can be achieved by relating runoff and reservoir storage to climatic inputs and hydrologic processes within a watershed.

Where the behaviour of a system becomes of interest, then a simulation model is developed to study that system over a time horizon. It must be mentioned that in contrast to optimization models, simulation models are "run" rather than "solved". Simulation models usually involve a given set of inputs and model characteristics which would be ran and the simulated behaviour observed.

Based on this background, Korn and Wait (1978) defined simulation as experimentation with models.

Another intriguing concept that has recently become relevant with models is the development of scenarios. Scenarios are plausible and internally consistent descriptions of possible future state(s) of a system. They explore trajectories of change from the present to a future state by considering many elements of a dynamic systems. Each scenario represents a possible storyline of how the future may turn out. It must be mentioned that scenarios are not forecasts or predictions, as they do not necessarily aim at projecting the most likely future condition. However, they help appreciate the consequences of alternative conditions, examine potential risks and opportunities as well as discover ways to respond appropriately to those risks and opportunities (Wagener *et al.,* 2006; Liu *et al.,* 2007). They may also be useful in analytical purposes to contrast the different possible evolutions in a system. Instead of depending on forecasts, scenarios provide creative and pliable approaches to preparing for the unknown (Schwarts, 1991; Van der Heijden, 1996).

From the list of reviewed publications, simulating the behaviour of a system and also developing possible scenarios of that particular system for futuristic outlook purposes are not a common practice especially in sub-Saharan Africa. For this reason, this thesis aims at employing these tools using conditions pertaining within the Bosomtwe District as a case study. This is expected to inform decision making processes and action plans concerning the management of the water resource (demand, use and sustainability) within the District.

1.2 Problem Statement

The water balance of Lake Bosomtwe has not been entirely understood even though some level of satisfactory results have been realized from past research activities. For instance, the findings of Turner *et al.* (1996) suggest that the reception of rainfall by and evaporation from the lake surface are the dominant constituents of the water balance. Shananhan *et al.* (2007), as a follow up, also identified changes in precipitation, cloudiness, temperature and changes in run-off related to vegetation to be the sensitive components responsible for the lake water level dynamics. The high variability in the contributions of identified factors for a particular outcome, coupled with their interdependence thus make future predictions highly improbable. There is therefore the need to adopt a scenario building approach and some necessary simulations for plausible futuristic outlook purposes.

1.3 Research Questions

1. How do the climatic conditions of the Bosomtwe catchment area affect its hydrology?
2. What are the dominant ecological factors influencing the hydrologic behaviour of the Lake Bosomtwe and how do they change spatially and temporally?
3. What are the anthropological and land-use drivers operating in the Bosomtwe catchment and how do these affect the hydrology of the lake?
4. What are the plausible repercussions of a statistically significant change in climate, ecological and anthropological drivers in the Bosomtwe catchment?

1.4 Aim and Objectives

The purpose of this research is to contribute to the pool of knowledge on Lake Bosomtwe's dynamics and propose strategies for its sustainable management.

Specific objectives are to:

- Identify the dominant factors influencing the hydrological behaviour of Lake Bosomtwe and its surrounding environment.
- Estimate the various water-balance components of the catchment for Lake Bosomtwe.
- Simulate the current water balance for Lake Bosomtwe
- Generate and simulate future water balance scenarios for Lake Bosomtwe.

1.5 Organization of Thesis

The first chapter gives a general overview of three concepts (namely modelling, simulation and scenario building) in relation to the project to be carried out. Specifics include the problem statement, research questions as well as aims and objectives. Chapter 2 is the literature review on the above mentioned concepts. Chapter 3 also looks at the methods employed in achieving the set objectives. Chapters 4 and 5 are the results and discussion respectively. Finally, Chapter 6 provides the conclusions and recommendation of this research.

CHAPTER 2 LITERATURE REVIEW SECTION

2.1 Introduction

Extensive literature on the concepts of hydrological / watershed modeling, simulation and scenario building as well as their applications (both in the developing and developed countries) were thoroughly reviewed. From the search carried out, it was apparent that at the global level, there is a plethora of significant research published in these thematic areas. However, on a comparative basis, much of these publications have focused on the developed countries (such as the United Kingdom, Australia, Norway, Germany, Canada and the United States of America). In view of this, there is relatively very little published work within sub-Saharan Africa. Incorporating that which was obtainable, it is important to mention that the majority of this literature review is based on literature which is not specific to the study area or region but do have some bearing and relevance in the assessment and understanding of the hydrodynamics of Lake Bosomtwe in the Ashanti Region of Ghana.

2.2 Hydrological Modelling

The seemingly simple concept of developing a general model that is applicable to similar real life systems such as catchments may be misleading when it comes to modelling in hydrology. While it is fairly simple to grasp the processes involved in the hydrological cycle, Lundin *et al.* (2000) point out that it is far from easy to quantify the processes involved within any catchment system. This is explained by the fact that there are variations in climatic, topographical, land types and land-use(s) as well as various man-made interferences within any particular catchment system and this makes it very difficult to construct general models that treat the whole hydrological cycle in any given catchment in the world. As such, most models developed in certain climatic or geologic region will only treat a component or part of the cycle (for example, runoff or ground water flow) and will often have difficulties when used in a different setting. The term “hydrological models” is thus used in the wide sense to mean all models describing the hydrological cycle or any of it major parts.

Considerable work has been undertaken in understanding and modelling the processes involved in the hydrological cycle, enabling models developed to address a wide spectrum of environmental and water resource problems (Singh and Woolhiser, 2002; Borah and Bera, 2003). However, Beven (2000) reports that general uses of hydrological models include:

- Understanding hydrological processes and their impact on each other,
- Quantifying non-measurable hydrological processes,
- Application to ungauged watersheds Hydrologic forecasting.

Viessaman and Lewis (2003) found out that hydrological models vary along numerous pathways: time step, spatial scale, whether the model simulates single events or on a continuous basis, and how dissimilar hydrological components are computed. Similarly, Singh (1995) also reported that catchment models can be classified on the basis of hydrological processes, scale (time and space) and method of solution (Figures 2.1 - 2.3). In describing processed based classification, Singh (1995) illustrated a model as having five components which include system (catchment) geometry, inputs, governing laws, initial and boundary conditions and outputs (Figure 2.4).

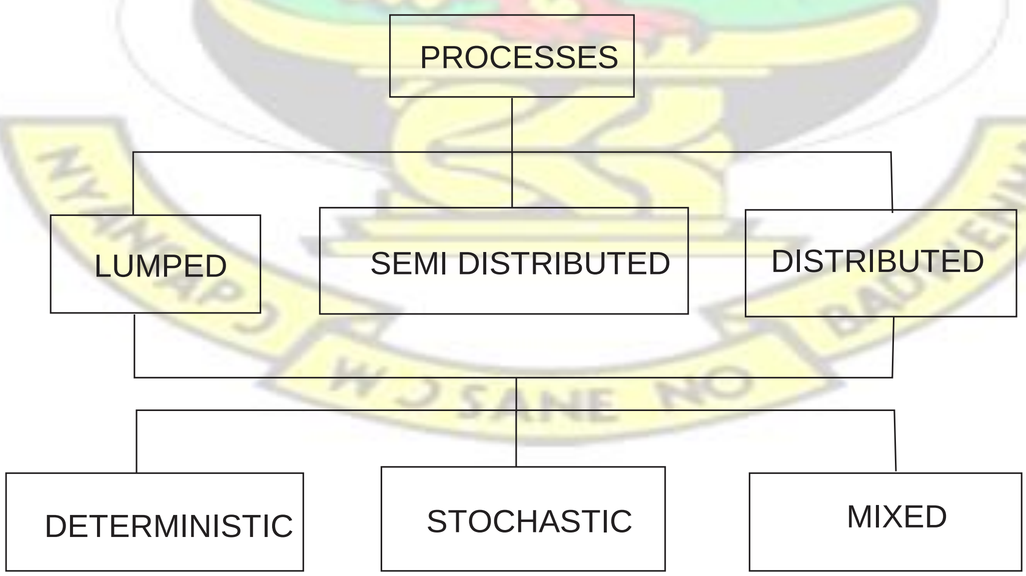


Figure 2. 1. Model classification based on process descriptions (Source: Singh, 1995)

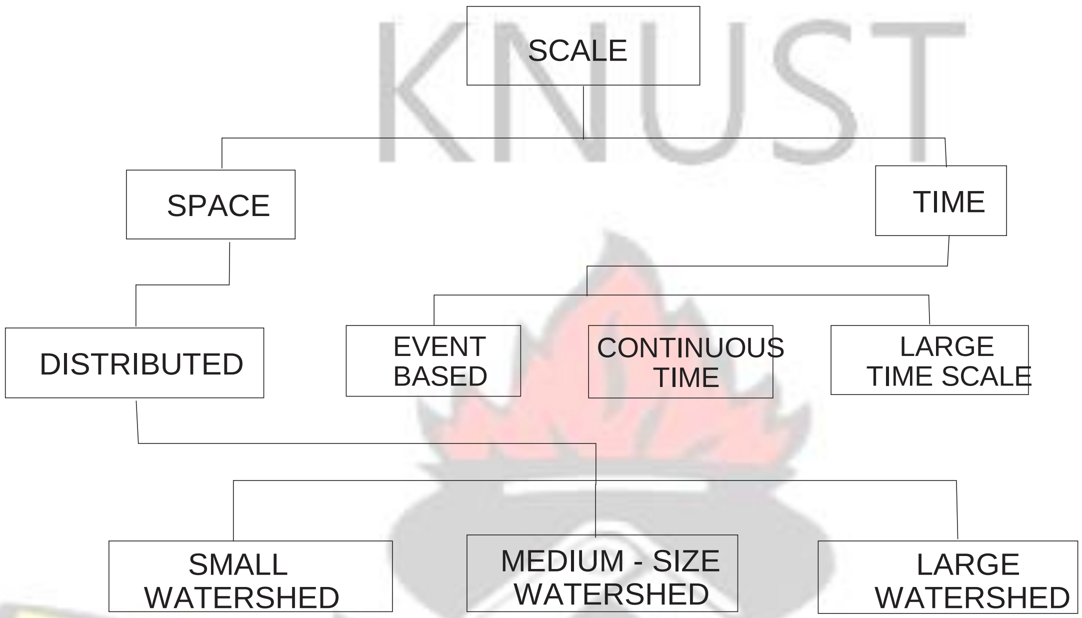


Figure 2. 2. Model classification based on space and time scales (Source: Singh, 1995)

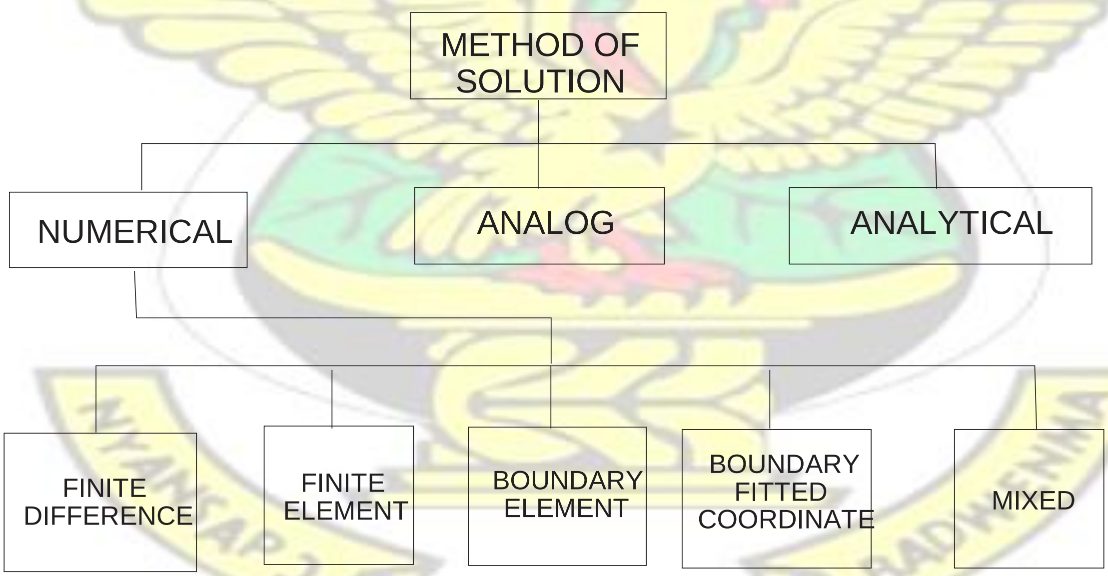


Figure 2. 3. Model classification based on solution technique (Source: Singh, 1995)

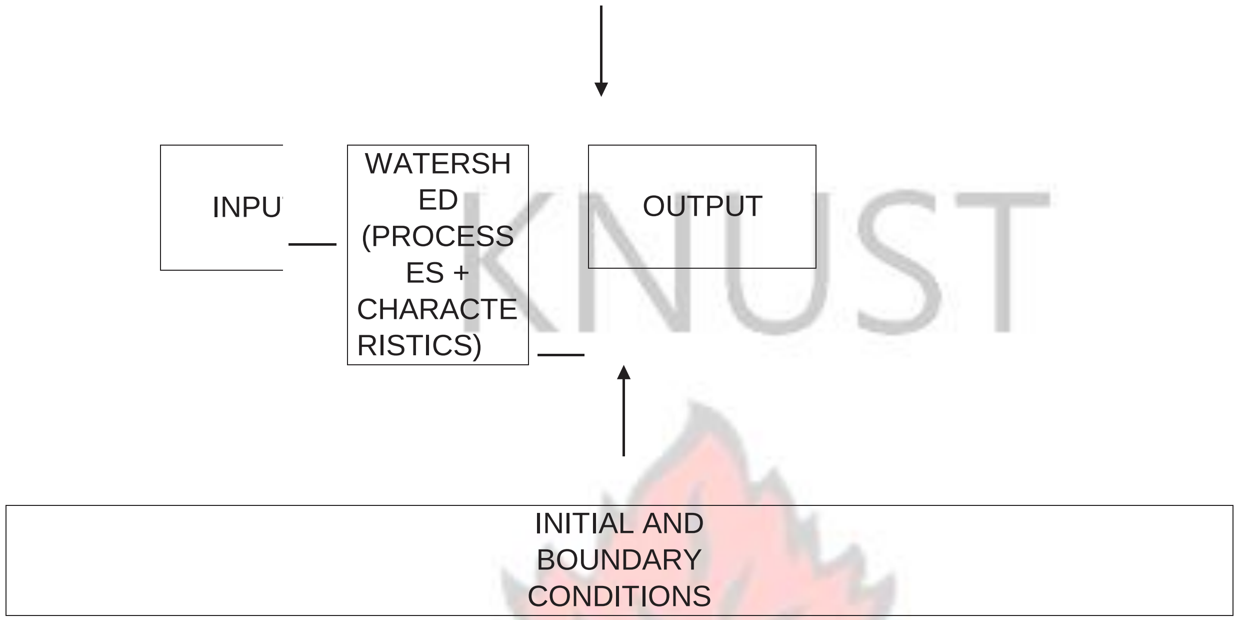


Figure 2. 4. Model components (source: Singh, 1995)

Depending on the type of model, these components are combined. This includes all hydrologic processes that contribute to the system (catchment) output. From the description of those processes, Singh (1995) remarked that models can be distinguished into deterministic, stochastic or mixed. Clark (1973) as well as Viessman and Lewis (2003) also reported that if one or more variables in the model has a probability distribution, then the model is classified as a stochastic model otherwise it is deterministic. According to Singh and Woolhiser (2002), a deterministic model will always produce superposable results for the same input parameters whereas a stochastic model will always produce dissimilar model response where one or more variables are chosen at random from the distribution. Depending on whether the model is based on physical laws or not, both stochastic and deterministic models can further be categorized into either conceptual, physical or empirical (Viessman and Lewis, 2003). As a further clarification, Singh (1995) and Singh &

Woolhiser (2002) mentioned that if all the model components are deterministic, the watershed model is deterministic. If all the model components are stochastic, the model is fully stochastic, and if only some components are stochastic then the model is quasi-stochastic. Singh and Woolhiser (2002) concluded by saying that the vast majority of models are deterministic, and that virtually no model is fully stochastic. Furthering on they observed that, in some cases, only some parts of the model are described by the laws of probability whereas other parts are fully deterministic. In such cases they conclude that it is fair to characterize them as quasi deterministic or quasi stochastic.

Without taking account of spatial variability in processes, input boundary conditions and system (catchment) geometry characteristics, a lumped model as noted by Singh (1995) is often expressed by ordinary differential equations. He adds that, while some processes are described by differential equations based on simplified hydraulic laws, other processes are also expressed by empirical algebraic equations in most lumped models.

Table 2. 1. System characteristics, component processes and governing equations of lumped and distributed models (source: Singh, 1995)

Input	System characteristics	Component Processes	Governing Equations	Output	Model Type
Lumped	Lumped	Lumped	[1]ODE	Lumped	Lumped
Lumped	Lumped	Distributed	[2]PDE	Distributed	Distributed
Distributed	Distributed	Distributed	PDE	Distributed	Distributed
Distributed	Lumped	Distributed	PDE	Distributed	Distributed

[1]ODE Ordinary Differential Equations; [2]PDE Partial Differential Equations

Examples of lumped models include HEC-HMS (Hydrologic Engineering Centre, 1981) and Hydrologic Model – HYMO (Williams and Hann, 1972).

On the other hand, distributed models such as European Hydrological system, SHE (Abott *et al.*, 1986) and National Weather Service River Forecasting System, NWSRFS (Burnash, 1995) according to Singh (1995) take precise and clear account of spatial variability of processes, input boundary conditions, and/or system (catchment) characteristics. It is however noted that in practice, the unavailability of data (field or experimental) forestalls the general formulation of distributed models. In many cases, models are quasi-distributed in which some processes, inputs and boundary conditions are lumped.

Diskin and Simon (1979), have also classified watershed models on the basis of time intervals as: continuous-time or event based, daily, monthly or yearly models. According to Singh (1995) in time steps models, one time interval may be used for input and internal computations and another for the output and calibration of the model. He adds that, models typically use computational time steps ranging from hourly to monthly and is often a function of process representation and the model's intended use. Singh (1995) furthers on to report that whereas event based models are designed for simulating a few or individual events on a short term basis, continuous models on the other hand simulate a behaviour over a long periods taking into account daily to seasonal predictions. These form the basis of planning models for water resources.

The spatial scale approach, according to Singh (1995) and Singh and Woolhiser (2002), can be used as a criterion to sort out models into small-catchment ($\leq$100km^2), medium-size catchment (100-1,000km^2) and large catchment (>1000km^2) models. They however caution that this classification is discretional and experimental rather than conceptual. It is also governed by data accessibility rather than physical meaning and that the essential import is the concept of homogeneity and the averaging of the hydrological processes.

Model accuracy is affected the most by space and time (Deliman *et al.*, 1999). Deliman *et al.* (1999) add that, when models are applied over very large areas, some parameters (for example soils and land use) will have to be lumped or averaged taking out the small-scale heterogeneities that will be found in the real world and this affects the predictions of runoff quality and quantity. They further observed that when time steps are too long, many physically based models do not function properly in terms of accuracy since the benefits of using distributed rather than lumped parameters are lost.

Notwithstanding the wide range of model types available, Woolhiser and Brakenseik (1982) suggest that watershed models are developed or chosen for a particular problem based on the following four features

- Accuracy of the prediction,
- Model simplicity,
- Consistency of parameter estimates
- The sensitivity of results to changes in the parameter values.

They conclude that the choice of model is usually made on the basis of the time frame available for development, input data resources and various other factors such as the experience of the modellers. Singh and Woolhiser (2002) also found out that, the choice of model to be used is mostly dictated by the availability of data. Principally all watershed models tend to satisfy the water balance equation.

2.3 Components of Watershed Models

2.3.1 Precipitation

Jutla (2006) identifies the precipitation component as the driving force in watershed models and reports that it may take the form of rain or snow on an hourly, daily or monthly time scale. Osborn and Lane (1982) also mention that the output from models are largely dependent on the input accuracy of this component. The National Research Council (1998) identifies three classes of precipitation inputs that can be used in models. They include historical precipitation, synthetic precipitation (designed and transposed storms) and stochastically generated precipitation.

According to NRC (1998), rainfall records (from rain gauges) for an extended period of time represents historical precipitation. The greatest advantage in the use of historical precipitation in watershed models is to analyse storm water responses in that, it presents a variety of scenarios of both antecedent conditions and precipitation intensity within the storm. This helps provide an understanding of the types of storms that are likely to results in severe flooding. A common problem with the use of data from rain gauges is having insufficient number of rain gauges in a network, thus assuming rainfall over an entire area is spatially homogenous. Ly *et al.* (2013) have pointed out that failing to adequately consider spatial variability in rainfall over an area will introduce errors into the overall hydrological model output.

Under synthetic precipitation, NRC (1998) differentiates between design storms and transposed storms. Design storms are synthetic rainstorms of a predetermined quantity, duration, temporal distribution and frequency. Synthetic design storms were originally developed for use on urban and small watersheds where the time concentration was generally less than three hours (Hicks, 1944; Jens, 1948; Keifer and Chu, 1957). On the other hand, transposed storms are historic precipitation events that have occurred outside of the watershed of interest, but within a region believed to have similar meteorological condition. The major application of transposed storms is the estimation of the probable maximum precipitation.

The Simulated precipitation is rainfall data generated from pre-existing rainfall data by some statistical means. This, according to Knapp *et al.* (1991), is conceptually the most desirable input for rainfall-runoff models for two reasons: firstly, it has the potential to address the spatial dynamics of storms and secondly the use of a long, stochastically generated series of rainfall avoids the need for analysis of the frequency of the simulated runoff.

In much recent times, rather than employing data from rain gauges to determine rainfall measurements, there is the introduction of the satellite-based rainfall products such as the NextGeneration Weather Radar (NEXRAD) which has the capacity to continuously capture spatial variation of precipitation over large areas. It must however be mentioned that this approach is far from perfect. Kalin and Hantush (2006) report that it is subject to several sources of error especially when estimating the actual amount of precipitation. Thus, Tancreto (2015) has provided guidance (both spatial scale and rainfall return frequency scenarios) for which the use of radar data would produce more accurate hydrological results.

2.3.2 Infiltration

The infiltration module is one of the most important and complex components. According to Ajayi (2004), the infiltration process has had a lot more attention in hydrological studies than any other component and this has resulted in the development of models that describe the process. Infiltration modelling approaches are often separated into three categories namely the physically based, approximate and empirical methods. Since physically based infiltration models have been developed by solving the governing equations for basic soil water movements, Rawls *et al.* (1993)

report that the physically based approaches require the solution of Richard's equation (Richards, 1931) which describes the flow of water in soils in terms of hydraulic conductivity and the soil water pressure as functions of soil water content for specified boundary conditions. However, solving this equation is not easy for many flow problems since it requires detailed data and the use of numerical methods. Numerical solutions as reported by Skaggs and Khaleel (1892) are costly, data intensive and require numerous field measurements thus are rarely used in practice. Consequently, for most applications, simplified versions of equations governing the infiltration processes are preferred (Rawls *et al.*, 1993). Some of these simplified versions include empirical models such as Kostiakov (1932), Horton (1940) and Holtan (1961), and approximate physically based models like those of Green and Ampt (1911) and Philip (1957).

Empirical models are inclined to be less limited by soil surface and soil profile condition assumptions, but more restricted by conditions for which they were calibrated, since parameters determined are based on actual field-measured infiltration data (Skaggs and Khaleel, 1982; Hillel, 1998). Physically based approximation equations, on the other hand, use parameters that can be extracted from soil water properties and do not require measured infiltration data. Turner (2006) observed that different approximate equations for infiltration result in different predictions for infiltration rate, ponding time and runoff time even when the same soil sample measurements are used to derive parameter value. It therefore holds that in determining which equation is suitable for a particular application, the assumptions, form and intent of each equation needs to be considered. Quite clearly, the classical point scale infiltration theory (eg., Green-Ampt Smith – Parlange, and the Philip Two Term model) is mostly applied in physically based hydrologic models (Fieldler and Ramirez, 2000).

2.3.3 Runoff

As the primary source of runoff, the hydrologic cycle has rainfall as its major component (Beven, 2001). According to Meher (2014), the rainfall to runoff transformation method has been described as one being highly complex, dynamic, non-linear and exhibiting both temporal and spatial variability. Meher (2014) adds that it is also affected by many parameters and often their inter-related physical factors. Thus for a given amount of rainfall on a watershed, the event may generate a high or low runoff depending on (besides other parameters) rainfall duration. This leaves the infiltration and evaporation losses depending significantly on how long the water remains in the watershed

Dingman (2002) reports that overland flow or surface runoff occurs under two conditions: either the soil surface is saturated from above (hortonian overland flow proposed by Horton 1933) or the soil surface is saturated from below (saturation overland flow proposed by Dunne and Black, 1970). Surface runoff process, as observed from the two generally accepted pathways, is significantly determined by the infiltration and percolation characteristics of the soil within the catchment. This suggest that surface runoff or overland flow process cannot be adequately understood if the infiltration behaviour is not properly studied. Thus the amount of rainfall that run on the surface as overland flow is influenced by infiltration amongst other biophysical factors (Ajayi, 2004).

The surface runoff process, being amongst the most extensively studied areas in hydrology, has contributed significantly to the understanding of processes that govern the transformation of rainfall to runoff. On a comparative basis, there are more documented studies of this process in the temperate regions (where most catchments are gauged) relative to the tropical zones where most catchments are ungauged (Chevallier and Planchon, 1993; van de Giesen *et al.*, 2000). It is important to mention that rainfall-runoff modelling approaches are various thus making classification a daunting task if not impossible. Beven (2001) makes mention of his attempt to draw an exhaustive list of rainfall-runoff models nearly 25 years ago and his abandoning of the task when he reached 100.

According to Beck (1991), the commonly used system of rainfall-runoff model classification includes the metric, physically based and conceptual models. In metric models, one considers the fact that a great amount of information is held in measured data that the model can extract to conduct predictions. Metric models treat the catchment as a single unit and relate its output to inputs using transfer functions. Transfer functions as reported by Huggins (1982) rely on the availability of historical data to develop an empirical equation. The first attempt to develop a mathematical method to transform rainfall into runoff was probably the rational method reported by Mulvaney (1851). This method relates the peak discharge to the catchment area, the rainfall intensity and an empirical coefficient to be defined for the catchment. This method is still in use to calculate the peak discharge of storms, especially in urban hydrology (Tolland *et al.*, 1998; Hua *et al.*, 2003). Sherman (1932) also reports of another method used called the unit hydrograph. According to Todini (1988), this is a linear method based on the principle of superposition and can therefore be applied to a complete hyetograph to produce a hydrograph and not only the peak discharge as with the rational method. Amorocho and Brandstetter (1971), report that the unit hydrograph method assumes that rainfall-runoff relation is invariant in time and does not depend on rainfall intensity. It also assumes that the variability of other outputs is small during the period of application. The geomorphological unit hydrograph is another approach which seeks to relate the unit hydrograph to geomorphological characteristics representing the channel network (Rodriquez-Iturbe and Valdes, 1979; Shamseldin and Nash, 1988). The applicability of a linear relation between rainfall and runoff, as assumed in the unit hydrograph method has however been proved not to be suitable in all cases (Amorocho and Brandstetter, 1971; Sivakumar *et al.*, 2001). Some authors according to Labat *et al.* (2000), have not only questioned the linearity of transfer functions but also its stationarity in time. Finally, artificial neural works have also been used recently to represent the transformation of rainfall into discharge (Maier and Dandy, 2000; Hsu *et al.*, 2002; Baratti *et al.*, 2003, Lallahem and Mania, 2003).

Maréchal (2004) reports that physically based models are developed following the bottom-up approach (Sivapalan *et al.,* 2003) and are based on a priori perception of the importance of the various physical processes and how they interact. He adds that physically based models are based on the laws of conservation of mass, momentum and energy. They solve differential equations for overland flow and channel flows, saturated and unsaturated subsurface flows and they link these subsystems to meet their boundary conditions. According to Xu *et al.* (2001), physically based models become valuable tools where detailed spatial information are of necessity. In spite of the perception that physically based should reflect observed physical processes, Beven (2001) has argued that it not currently possible to build this true representation and that some level of empiricism has to be introduced.

Conceptual models according to Young (2003) vary from metric models in that they are constructed from a theoretical representation of the hydrological process. He adds that some conceptual models can be very similar to data-based mechanistic models. The distinction is that, with conceptual models, their structure has been decided according to the developer's perception of the important processes. Maréchal (2004) also points out that, conceptual models differ from physically based models in that they are built to be a simplification of a complex reality. Clearly most conceptual models developed have hailed from Europe and are data intensive. Typical examples include Stanford (Crawford and Linsley, 1966), Hydrologiska Byråns

Vattenbalansavdelning - HBV (Bergstrom and Forsman, 1973) and TOPMODEL (Beven and Kirkby, 1979). However Schwab *et al.* (2002), report of another method for computing runoff volume from watershed called Soil Conservation Service Curve Number (SCS-CN) model. They add that this model has been widely applied in the United States due to its simplicity. The Curve Number (CN) method is an approach based on relationships among rainfall, land characteristics and streamflow, which was developed from empirical investigations on small agricultural watershed and appeared in the US soil Conservation Services' National Engineering Hand book in the mid 1960's (Mockus, 1972). With the development and utilization of Geographic Information System (GIS) in hydrological studies, ArcCN-Runoff has been developed by Zhang and Huang (2004) in Arc GIS to enhance the accuracy and precision of runoff estimations.

2.3.4 Evapotranspiration

According to Jutla (2006), evapotranspiration plays a major role in defining the water balance in arid and semi-arid regions. It represents two components of the water cycle: evaporation (which is the loss of water from the surfaces of soils and waterbodies) and transpiration (which is the consumptive use of water by plants). Evapotranspiration flux move large quantities of water from the soil back to the atmosphere. Allen *et al.* (1998) report that evapotranspiration is affected by a number of factors including weather parameters (such as temperature, solar radiation, wind speed and relative humidity) as well as management and environmental factors (such as pest and disease control, soil fertility and salinity). Thus a process-based understanding of evapotranspiration is needed to place a quantitative value on the likely changes in evapotranspiration as a consequence of climate and land surface change (Choudhury and DiGirolamo, 1998; Hutjes *et al.*, 1998).

Direct measurement of evapotranspiration is costly and difficult, thus requiring skilled personnel to obtain accurate measurements (Allen *et al.*, 1998). To simplify evapotranspiration measurements, a number of models have been developed to estimate it. Many of these have been deduced empirically through field experiments (Thornthwaite, 1948; Blaney and Criddle, 1950; Jensen and Haise, 1963), while others (Penman, 1948; Hargreaves, 1974; Hargreaves and Samani, 1985) have been developed from theoretical approaches involving a combination of the energy and mass transfer methods. It is also important to mention that many of the existing evapotranspiration models were developed in the arid and semi-arid environments with most of the comparisons of models in the United States focusing on the Great Plains of the Midwest or the West (Hansen *et al.*, 1980; Hatfield and Allen, 1996; Jensen *et al.*, 1997). Others were also developed on the east coast of United States of America (Thornthwaite, 1948), Europe (Penman, 1948; Makkink, 1957; Turc, 1961) and in Australia (Priestley and Taylor, 1972; Linacre, 1977).

According to Fontenot (2004), evapotranspiration models are usually categorized into three basic types namely temperature, radiation and the combination (Jensen *et al.*, 1990; Dingman, 1994; Watson and Burnett, 1995). Jensen *et al.* (1990), report that temperature based models generally require air temperature measurements as the sole meteorological input to the model (Thornthwaite, 1948; Doorenbos and Pruit, 1977). Radiation based models, for example Turc, (1961) and Hargreaves and Samani, (1985) are typically fashioned to employ some of the energy budget concept components and usually require the measurement of some form of radiation. Finally, combination models for example Penman (1948) incorporate elements of both energy budget and mass transfer to give very accurate results (Jensen *et al.*, 1990). Jensen *et al.* (1990), and Allen *et al.* (1998), report that the Penman family of models is regarded as the most common combination model in use in much recent times. At present the development and use of remote sensing techniques to estimate evapotranspiration has been reported by Courault *et al.* (2005).

2.4 Modelling Approach

Chapra (2003) recommends that a good modelling approach will be one that is adaptive; starting as a simple model and then progressively becoming complex as additional data are included. Elshorbagy and Ormsbee (2005) also add that simulation tools which can provide realistic descriptions of complex systems strongly need to be explored and that the process of model development should involve water resource managers and operators so as to boost confidence in the results obtained after modelling. They therefore propose that a model should have at least these seven characteristics:

1. Watershed or any hydrologic system should be described and simulated in a simple manner.
2. The model should start out simple, relying on the available data and be expandable to benefit from additional data as they become available
3. It should be adequately dynamic so as to cope with the nature of hydrologic systems
4. It should have the ability to simulate both linear and non-linear processes
5. It should have a way of representing feedback mechanisms in order to handle counterintuitive processes
6. It should have the ability to model human intervention and any shocks that the system could encounter.

7. It should have the ability to simulate different policy or management scenarios for better decision – making.

While it might appear almost impossible to have all of these characteristics embodied in one modelling approach, Elshorbagy and Ormsbee (2005) have mentioned that, with the emergence of system dynamics approach this is now possible.

Object-oriented modelling (which is based on the system dynamics approach) is a means through which real world concepts are organized in models to solve problems (Rumbaugh *et al.*, 1991). It is a way to organize software as a collection of discrete objects that incorporate both data structure and system behaviour (Simonovic *et al.*, 1997). Data are prepared into discrete, recognizable entities called objects. These objects could be concrete (such as a river reach) or conceptual (such as a policy decision).

2.4.1 System Dynamics (SD) modelling process

The process of building a system dynamics model is an iterative one in which the model is built in steps of increasing complexity until it simulates the natural behaviour of the natural system under consideration. According to Randers (1996) and Stave (2003), the modelling process in system dynamics can be divided into four stages.

Stage one is called the conceptualization stage and that determines the objective of the problem. The general perspective and time horizon of the problem are established in this stage of model development. The conceptualization stage helps to draw the attention of the analyst toward closed loops of cause and effect and stress the distinction between stocks and flows. Causal loops and hence feedback relationships are determined at this stage.

Stage two known as the formulation stage, casts the chosen perception of the model into a formal representation. One of the important steps to be followed is to determine the parameters of the model. Some parameters may have fixed measurable or known values in the system while others may vary with time or space. It is essential to identify both types of parameters in the system.

Stage three, called the testing stage follows after the successful identification of the model parameters. This stage is intended to establish the quality of the model by comparing the results obtained from the model with field or real world data sets. This procedure is also referred to as calibration. Also the goal of this stage is to identify the weak points in the feedback relationships and possible errors in the dynamic theory of the system.

Stage four called implementation, is directed towards the stakeholders who are intended to use the model. The response of different policies or scenarios of the problem under consideration are tested in this stage.

2.4.2 Application of SD approach to water resources

According to Jutla (2006), system dynamics modelling approach has been used in economics, business management, and the social sciences for a long time. However, the potential use of such an approach in water resources was documented for the first time in proceedings of the 20th anniversary conference on water management which was held in Seattle in 1993. Lee (1993) emphasized that model building in hydrology is an art and suggested that models should be built in two stages namely model conceptualization and model programming. These two stages according to Jutla (2006) are represented effectively using a system dynamics modelling approach and so hold the potential to be an excellent tool for instructing on hydrological modelling.

On a comparative basis to traditional modelling approaches, the application of system dynamics approach (even though successful) is very limited. Some of the successes include that of Simonovic (2002) who used the system dynamics modelling approach to model world water resources. The research paper focused on prediction of the impacts of various scenarios of water demand and supply across different continents. Similarly, Li and Simonovic (2002) successfully adopted system dynamics approach to predict floods in two prairie watersheds. Their study concluded that system dynamics modelling is a useful tool in understanding complex hydrologic relationships in the watershed. Their study also concluded that system dynamics based hydrologic models are easy to calibrate, validate as well as perform sensitivity analysis on. Elshorbagy *et al.,* (2005) also constructed a hydrologic model based on system dynamics principles and used the model for the assessment of sustainability of a land reclamation strategy. It was concluded that the flexibility in building models with system dynamics facilitated the understanding of the interrelationships among various hydrologic processes occurring in the watershed.

2.5 Scenario Building Overview

The official scenario planning is reported by Schwartz (1991), to have originated from the U.S. Air Force devisers' efforts to predict their opponent's actions during World War II. This enabled them prepare alternative counterplans to be used should a particular scenario occur. These scenarios were developed by the RAND Corporation as part of military strategy studies conducted for the U.S government. One of these RAND Corporation military strategists, Herman Kahn, later refined and employed the scenario building approach as a business planning tool in the 1960's (Fahey and Randall 1998). Pierre Wack advanced scenario building to a whole new level in the 1970's when he created alternative futures for Shell's oil enterprise. By so doing, Shell managed to stay afloat and maintained its position in the industry during the oil embargo from the period of 1973 to 1974. According to Fahey and Randall (1998) Shell has been credited for the widespread adoption of scenarios in corporate setting and continues to develop scenarios under the guidance of Pierre Wack and his group. The use of scenario building was later extended to governments when Peter Schwartz and some of his colleagues formed the Global Business Network; an organization that helps companies gain insight into the future (Schwartz, 1991; Means *et al.,* 2005). Mahmoud (2009) has also reported of the emergence of applying the scenario building approach in environmental studies.

Climate change has become one of the big challenges facing the twenty first century considering the logic that, climatic changes may have direct and indirect impacts on the natural environment as well as on human societies. It therefore holds that the hydrology and water resource of many communities may be affected since they are closely related to climate. According to Marttila *et al.* (2005), research on climate change impacts on nature and society provides the knowledge needed by planners, managers and policy makers to assess adaptation possibilities and to direct adaptation efforts to vulnerable geographic regions. This is necessary to reduce the negative impacts and to take advantage of possible opportunities associated with climate change.

Climate change impact on water resources can be studied with the use of climate scenarios and hydrological models. It must be mentioned that considerable effort has been expended on developing improved catchment hydrological models that mimic nature and yet still, no one environmental model has accurately made forecasts of future hydrologic conditions since the environment is constantly changing. Schwartz (1991) therefore suggests that, rather than relying on predictions made from models that mimic nature, it is prudent to employ scenarios in order to plan for an uncertain future.

A scenario is, thus, defined by many authors as a description of a possible future situation and that includes the path of development which may lead to that future situation. In contrast to a conceptual future, which merely represents a hypothetical future state of affairs, a scenario describes the developments, the dynamics, and the moving forces from which a specific conceptual future results (Greeuw *et al.*, 2000). It is important to lay emphasis on fact that scenarios are not forecast or predictions or projections. Rather, they are stories with a logical plot about how the future may unfold (Cole, 1981; Miles, 1981; Schwartz, 1991). Scenarios thus consider a number of believable, and even unlikely, alternatives for the future to help us appreciate the impacts stemming from alternative conditions, assess potential risks and opportunities and identify ways to respond to those risks and opportunities (Wagener *et al.*, 2006; Liu *et al.*, 2007).

In traditional forecasting applications, predictions as produced by deterministic models (McCarthy *et al.*, 2001) are typically oriented towards the most likely future and this is done in an attempt to simulate the future with a high level of accuracy thus giving an illusion of certainty. Forecast as reported by Mahmoud (2009) are therefore geared towards predicting the “official future”. Figure 2.5 illustrates the relationship between scenarios and forecasts as a function of future planning. According to Schwartz and Ogilvy (1998), one purpose of a scenario is to challenge the idea of an “official future” which tends to be unsurprising, non-threatening, stable in growth, and poses no remedies to current crises.

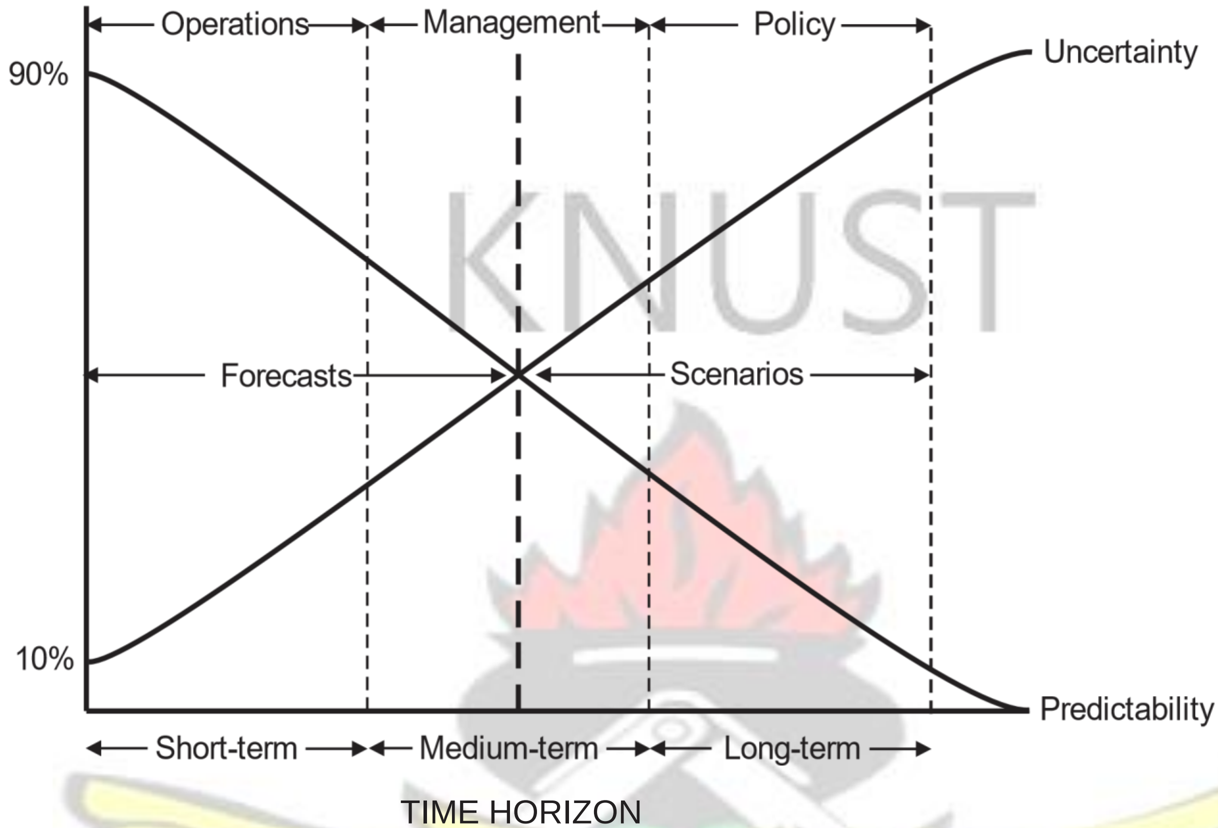


Figure 2. 5. Relationship between forecasts and scenarios (source: Van der Heijden 1996 and Leney et al., 2004)

Again the terms scenario and alternative future as observed by Mahmoud (2009) have been used interchangeably in literature. However, there is a difference in meaning of these words when describing the future. An alternative future illustrates the state of a system at the end of a time horizon period extending into the future, and a scenario describes the shifts and changes in system condition that produce such an alternative future. Therefore each scenario represents a projection path that is as long as the planning horizon time – frame and each alternative future is the endpoint of its respective scenario (Figure 2.6).

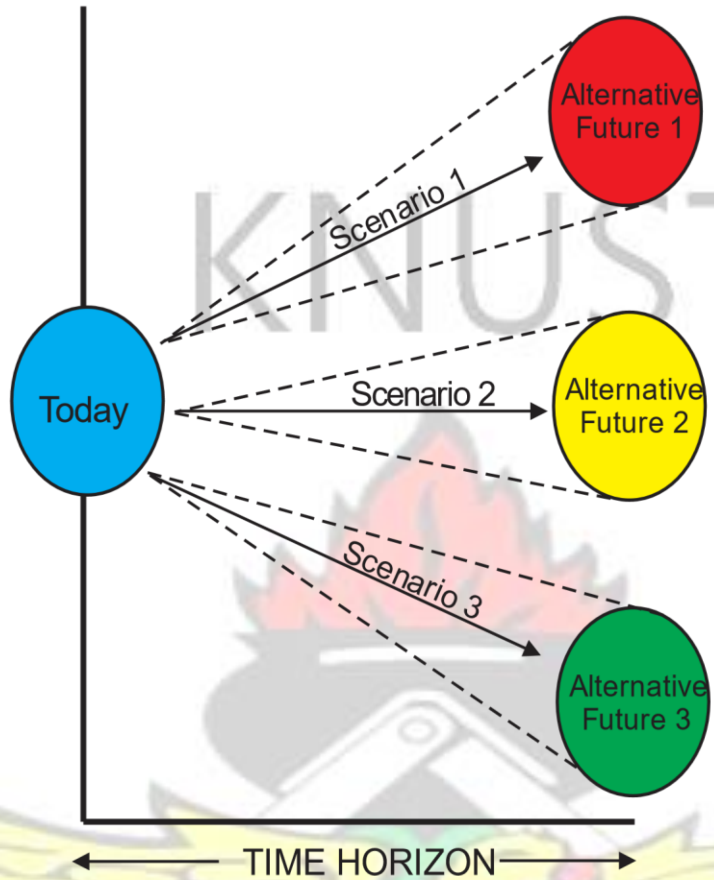


Figure 2. 6. Relationship between scenarios and alternative futures (adopted from Mahmoud 2009)

2.6 Water balance Modelling and Scenario Building in Africa

From the list of reviewed articles, it is observed that there is a plethora of published works on the water balance of lakes in other continents compared to Africa and these studies are carried out on a regional basis. Typical examples include peer reviewed articles on Lakes Balaton, Geneva, and Constance amongst many others in Europe. Another observation made is that, but for Lakes Victoria, Malawi, Tana and a few others, majority of the published works in Africa often concentrate on a component of a watershed rather than a holistic water balance study of the various components within a particular catchment. Interestingly, there's no mention of scenario building in most of these published works in Africa since the goal of modelling is towards validating the suitability of modelling approaches and making future predictions.

Using a spread sheet hydrological model, the water balance of the closed freshwater Lake Awassa (Ethiopia) was estimated by Ayenew and Yemane (2006). Monthly Precipitation, evaporation and river discharge data were the model's input. From their results the simulated and observed lake water fitted well for the period of 1981-1999. However, this was not the case for the years thereafter. To account for the drift, Ayenew and Yamane (2006) explained that the average combined effects of land-use changes and neotectonism had affected the long term water balance. Probing further with a detailed investigation of the subsurface hydrodynamics (including the effect of land-use change and tectonism on surface water and groundwater fluxes) they report that their water balance model was suitable for water management and that their findings were expected to contribute positively to the sustainable use of the water resources in the catchment.

Russel and Johnson (2006) also modelled the water balance of Lake Edward (Uganda-Congo) considering the fact that it is one of the least studied of the great lakes of East Africa, and very little is known of its physical hydrology. Stable isotope data and previously published estimates of

Lake Edward's water balance were used to constrain the physical hydrology of the lake, and particularly the relative proportion of surface outflow to evaporative water losses. Stable isotope calculations suggested that Lake Edward loses roughly 50% of its water income by evaporation, while reviews of published hydrologic data together with our calculations suggest that evaporation comprises about 54% of water losses. According to Russel and John (2006), the similarity of these two sets of calculations lends credence to their validity, and provides a new water budget for the lake. They also add that their results have important implications for the chemistry and hydroclimatic sensitivity of Lake Edward.

Similarly the water balance of the Upper Blue Nile in Ethiopia was modelled using a grid-based model that required limited inputs and a few parameters by Conway (2009). Operating on a monthly time step, the model investigated spatial variability in the sensitivity of runoff changes for rainfall and potential evaporation. Estimates of rainfall and potential evapotranspiration were predicted using 10 minute resolution grid cells as model inputs. In the model, vegetation cover as well as soil characteristics were not explicitly treated. Calibrating and validating the model to reproduce mean monthly runoff over thirty seven years (1953-1987), the results suggested that seasonal rainfall distribution strongly affected runoff sensitivity. The study ended discussing the model's performance and the possibility of further development in the future.

Finally, Deus *et al.* (2013) estimate the water balance of Lake Manyara (located within the East African Rift of northern Tanzania) with limited *in situ* data. Employing a distributed conceptual model which is driven by remote sensing data, the study focused on examining the spatial as well as the temporal variability of water balance parameters within the catchment. Satellite gravimetry GRACE data was used in verifying trends of the inferred lake level changes. With low rainfall and high evapotranspiration (which is characteristic of semi-arid climates), the results suggested that the lake experiences very high spatial and temporal variations in the simulated parameters. It was also observed that the lake's water balance and the GRACE equivalent water depth displayed very similar trends: a decrease after 2002 followed by a sharp increase in 2006-2007. This is reported as confirmation of the 2006-2007 Indian Ocean Dipole fluctuation responsible for replenishing the groundwater resources of East Africa. From their work, they conclude that, even in very complex climatic settings, water balance modelling can be successfully performed using remotely sensed data.

2.7 Previous work on Lake Bosomtwe

The water balance of Lake Bosomtwe was first studied and published by Turner *et al.* (1996) even though some research work on the lake such as the Lake Bosomtwe impact crater (Jones *et. al*, 1981) had been published earlier on. The model used during the study was based on records of the lake's water level between 1938 and 1980 and the findings of their work identified rainfall and evaporation as the dominant factors influencing the lake's water balance.

Upon scrutiny of the published work, Shanahan *et al.* (2007) described the model employed by Turner *et al.* (1996) as one that overestimates various parameters involved in the study since all the controlling factors of historical lake level changes were not properly addressed. Shanahan *et al.* (2007) thus improved upon the work by studying the seasonal as well as monthly changes in the lake level water budget, providing a more elaborate yet flexible physical parameterization of hydrological processes that could easily work with prehistoric periods, assessing the strength of a number of evaporation models in simulating lake water levels, expatiating on the controls of lake's water level fluctuation and finally extending the model simulation from 1938 to 2004.

Subsequent scrutiny of the published work of Shanahan *et al.* (2007) by Amo-Boateng (2011) revealed that the model employed by Shananhan *et al.* (2007) lumps land cover into static percentages, creating inflexibility in changing land use patterns. Moreover, the model was calibrated by comparing it with other basins that differ in characteristics to that of Lake Bosomtwe and thus did not provide satisfactory grounds for evaluation of the model.

Amo-Boateng (2011) thus proposed and employed a semi – distributed modelling approach which was to allow for the accounting of all spatio-temporal variables without increasing the complexity of neither model nor over-generalization of the water balance model of the lake. Even though Amo-Boateng (2011) successfully produced satisfactory results, the conceptual framework upon which his model is built on is inadequate since the hydrologic profile of the lake has been poorly appreciated. As such, it fails to account for water losses as a result of water withdrawals and evapotranspiration from the catchment area's land surface. Again, his hydrological modelling approach by nature was analytical and involving the use of traditional models. Nashon and Kiema (2011) remarked that such approaches are not effective in reaching a wider cross-section of readers from various disciplines because they hardly show clear structural relationships between the key drivers of change in the lake ecosystem. In addition, the numerous results obtained remain detached and thus need to be integrated into a holistic framework.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Desk study and field visits

Extensive literature on lakes, reservoirs, hydrology, modelling, water balance, watershed modelling, simulation development, and scenario building hydrological models have been thoroughly reviewed. From these reviewed literature, research gaps were identified that set the basis for the objectives and methodology of this research. The methodologies adopted therefore follow standard scientific procedures and can be compared with similar research conducted around the globe. Literature considered was mainly peer reviewed articles from the database of the following scientific journals and resources: African Journals Online (AJOL), CAB Direct, ScienceDirect, ELDIS, Elsevier and Ghana Government reports. Field visits were also carried out to make observations, identify relief features as well as capture co-ordinates points of those features that would have some bearing on the study.

3.2 Description of the study area

As an inland freshwater lake within the landmass of the Ashanti Region - Ghana, Lake Bosomtwe is located at 6º 30’ N, 1º 25’ W which is about 30 km south east of Kumasi (in the northern tip of the Adansi Mountains). The lake occupies a meteoritic crater which is estimated to have been formed approximately 1.07 million years ago (Jones *et al.*, 1981; Koeberl *et al.*, 1998). The crater has an estimated diameter of about 10.5 km at the rim with a well-defined spillway believed to have been formed during the Holocene when the lake water overtopped the crater. Recent estimates suggests that the lake is presently situated some 120 m below the crater rim. Having no surface outlets, it is believed that the lake drains internally and also has a bedrock of crater walls hydrologically isolating it from the regional aquifer. The lake at present is estimated to have a surface area of about 52 km^2 and a drainage basin area of about 106 km^2 (Turner *et al.*, 1996).

According to Shanahan *et al.* (2006), the catchment area is largely vegetated with tropical dry forest even though some portions have been reduced to farmlands in recent times. Maximum water depth recorded is about 76 m and this has been observed to occur across a broad zone in the lake's centre.

The climatic conditions around the lake are largely influenced by the West African monsoon and the seasonal movement of the intertropical convergence zone (ITCZ). Long term monitoring of weather variables within the Ashanti region suggest that precipitation received annually is about 1269 mm with a variation of more than 15% over the last 70 years. Temperatures vary slightly ($\pm$ 1.5 ^{o}C) around a mean of 26 ^{o}C with lower temperatures occurring annually between June and October as a consequence of cloudiness. Shanahan *et al.* (2007), acknowledging the hydrological isolation of the lake system, also reported that the lake water level responds sensitively to rainfall and evaporation and thus hold the potential to be a sensitive recorder of past hydrologic conditions.

According to the belief of surrounding communities, the Lake is a sacred place. As the dwelling place of a deity, several sacred sites that are of cultural value to inhabitants abound around the lake (Lissewski, 2003). Fishing from the lake is the predominant source of livelihood for these communities living around the lake. Besides fishing, the lake serves as a source of water for both domestic and irrigational purposes. Transportation and tourism are other economic and social opportunities that the lake offers. Sadly, tourism related developments have been concentrated only around Abono (Prakash *et al.*, 2005).

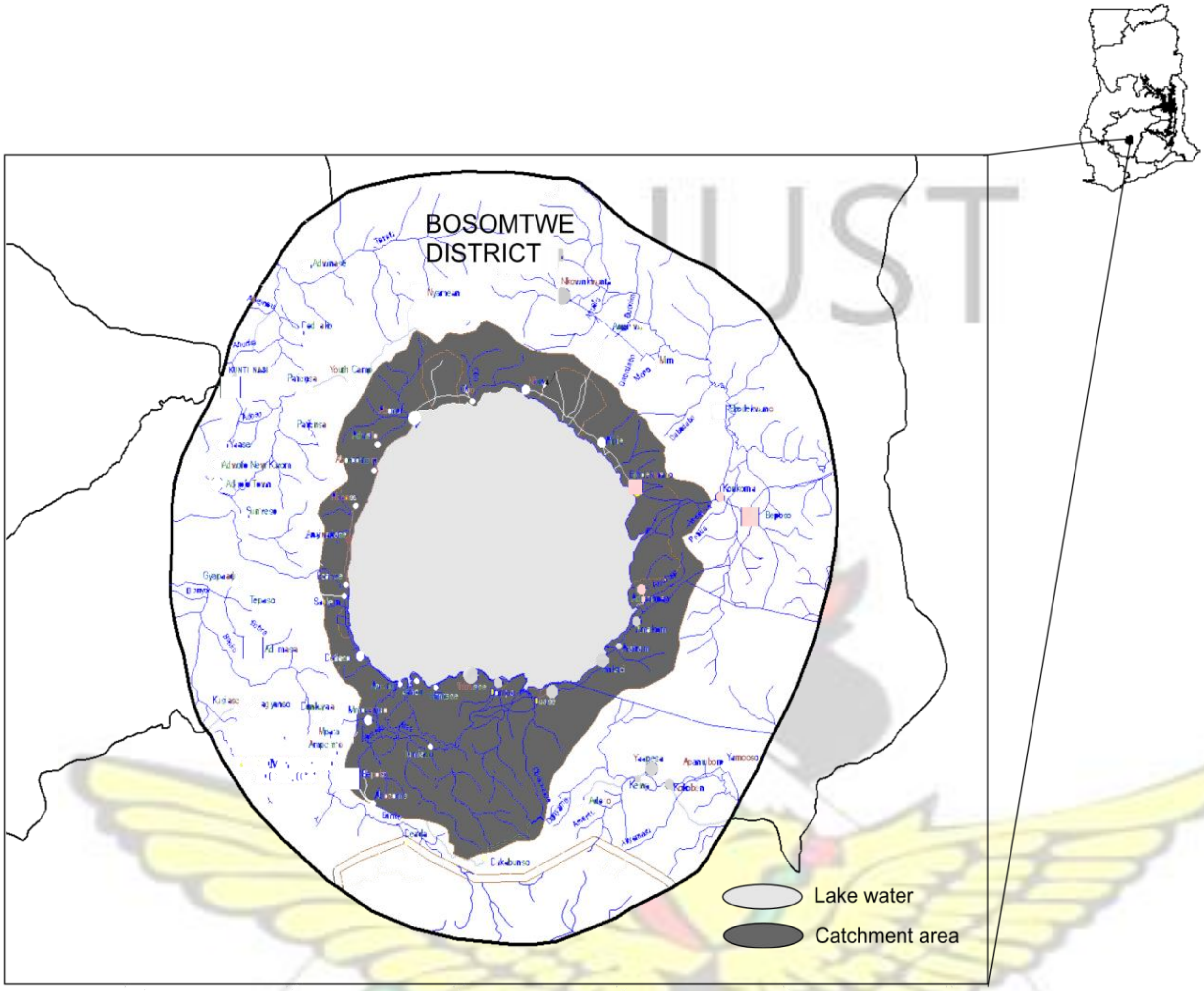


Figure 3. 1. Map showing the catchment area of Lake Bosomtwe.

Figure 3. 2. Aerial photograph of Lake Bosomtwe (adopted from Dutch, 2004; Amo-Boateng 2011)

3.3 Data collection

Relevant secondary data sourced from previous studies conducted within the Bosomtwe District were obtained primarily from the KNUST repository and also as described above. To complement the secondary data, some primary data were also acquired from the Meteorological Services Department, Accra - Ghana and the Hydrological Services Department – Kumasi.

Meteorological data

Since Turner *et al.* (1996) report of a strong correlation between regional rainfall pattern and the lake's water level records, it was therefore assumed that the climatic data collected from the

Kumasi Airport about 37km away conforms to that of the lake. Therefore, the data used in the study included rainfall records, air temperature records, and relative humidity records from the period of 1984 to 2013. Rainfall, temperature and relative humidity data for Kumasi were obtained from the Meteorological Services Department, Accra whereas the Lake Bosomtwe's water level data was also obtained from the Hydrological Services Department - Kumasi. Average monthly wind speed data for the Ashanti Region was also obtained from RETScreen database (https://eosweb.larc.nasa.gov/cgibin/sse/retscreen.cgi?email=rets%40nrcan.gc.ca&step=1&lat=6.7&lon=-1.6&submit=Submit). Similarly monthly estimates of extraterrestrial radiation from the period of 1984 to 2009 were obtained from Amo-Boateng (2011). This data was complemented with the average monthly estimates also obtainable from FAO (http://www.fao.org/docrep/x0490e/x0490e0j.htm#annex 2. meteorological tables). Finally, solar radiation estimates were obtained partly from Amo-Boateng (2011) as well as Soil Water Assessment Tool (SWAT) database (http://globalweather.tamu.edu/home/view/28433).

Satellite imagery and associated data

Images of the lake, catchment delineation and mensuration as well as land use classifications data were also obtained from Amo-Boateng (2011).

3.4 Model development, Simulation and Scenario building

3.4.1 Conceptual schematic diagram on which the model is built

With reference to the findings of Amo-Boateng (2011) and also based on observations made during field visits, a conceptual schematic diagram for the model was developed. The conceptual framework was built with the understanding that evaporation occurs on a daily basis and at all temperatures. Plants as well as the lake lose water to the atmosphere by this process. When the water vapour gets into the atmosphere, it condenses and falls back as rain. On the event of rainfall, a certain portion of rainwater falls directly on the lake surface whereas the remaining fall in the lake's catchment. This portion of rain that fall in the catchment has a certain portion intercepted by plants and eventually gets evaporated whereas the remaining infiltrate into soil. Again plants can act as water pumps and get water from the soil transpired. When the amount of rainfall is greater than the amount of infiltration, runoff or overland flow occurs (Horton, 1940) and the storm water finds its way into the lake. Considering the nature of the catchment landscape and the situation of communities within the lake's catchment area, it was very possible that water withdrawals (directly or indirectly) could significantly influence the lake water level dynamics. Thus the differences in volumes of input and output sources would account for the water balance of the lake as illustrated in Figure 3.2.

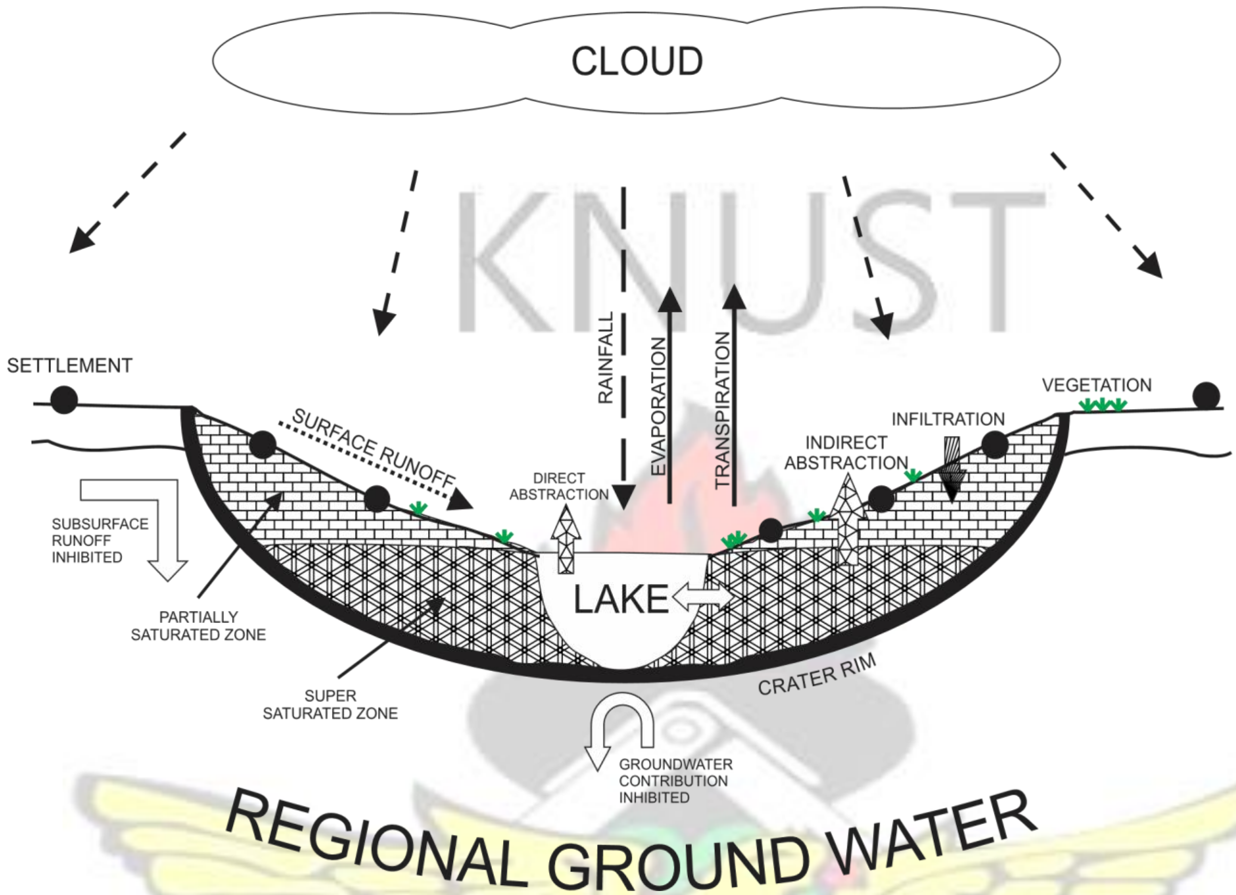


Figure 3. 3. Conceptual diagram illustrating the cross sectional hydrological profile for Lake Bosomtwe.

3.4.2 Model formulation and approach

Rather than employing traditional models such as the HBV model (Bergström and Forsman, 1973), STELLA Systems Thinking for Education and Research software was chosen. This user-friendly software allows the users to create and link observed processes in a graphical interphase using stocks, flows, converters and connecters, thus making the process of modelling more practical (High Performance Systems, 2000). Rainfall, surface runoff, direct evaporation from the lake surface, evapotranspiration from the land surface and population growth are identified as flows whereas population and volume of lake water are considered as stocks. Other factors such as temperature, extra-terrestrial radiation, solar radiation, humidity etcetera are considered to be converters. Connecters are then used to establish relationships between these variables as shown in figure 3.3. With such flexibility in modelling, a semi-distributed modelling approach was adopted in this study. This was to allow for the accounting of all spatio-temporal variables without necessarily increasing the complexity of neither model nor the over-generalization it. In this semi distributed model, all meteorological variables are assumed to be even over the entire catchment. Land-use and soil characteristics are however considered as distributed.

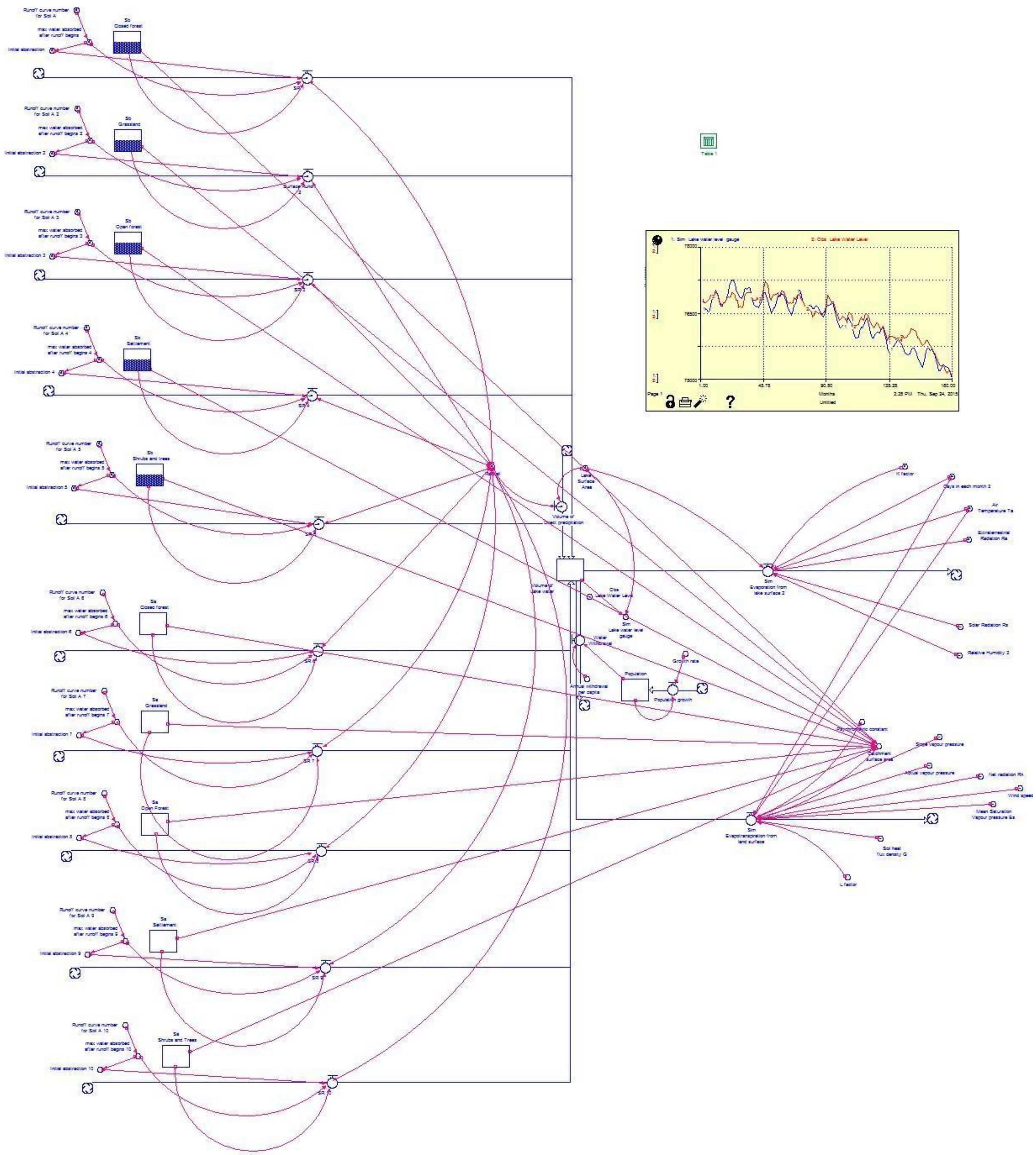


Figure 3. 4 STELLA model developed for the water balance of Lake Bosomtwe

3.4.3 Mathematical formulation of model components

3.4.3.1 Rainfall Estimation

Rainfall of Kumasi from 1984-2013 were organized on a spreadsheet using Microsoft Excel. The total monthly rainfall values for the aforementioned period were determined and used as an input for the model.

3.4.3.2 Runoff Estimation

Surface runoff estimates were computed applying the Soil Conservation Services Curve Number (SCS-CN) method considering that the SCS-CN method is simple to apply to a variety of watersheds and yields consistent results for particular land use categories. Accordingly, the storm runoff depth, Q for the Bosomtwe catchment was estimated by

$$Q = \frac{(P - Ia)^2}{(P - I_a + S)}$$

Where:

- Q is the runoff or discharge
- P is the storm rainfall depth
- S is the maximum potential retention and
- I_a is the initial abstraction (usually 0.2 * S)

The equation has a single parameter S which is related to Curve Number by

$$S\ (\text{mm}) = \frac{25400}{CN} - 254$$

It must be mentioned that, rather than the conventional constant of 0.2, a ratio of 0.05 was used in the calculation of S because the ratio 0.2 was not corroborated by the least squares fitting routine performed by many investigators for either humid or arid watersheds (Hawkins *et al.*, 2002)

3.4.3.3 Evapotranspiration estimation

This component was divided into two sub-components. One component focused on direct evaporation from the lake surface area whiles the other focused on the evaporation and transpiration from the catchment land surface area.

3.4.3.3.1 Direct evaporation from the lake surface

Evaporation from the lake surface was estimated using the standard Penman evaporation model which was slightly modified by Valiantzas (2006) to eliminate the wind data. The simplified Penman evaporation model, as given by Valiantzas (2006) is written as:

$$E \approx 0.047\mathrm{Rs}\sqrt{\mathrm{Ta} + 9.5} - 2.4\left(\frac{\mathrm{Rs}}{\mathrm{Ra}}\right)^2 + 0.09\ (\mathrm{Ta} + 20)(1 - \frac{\mathrm{RH}}{100})$$

Where

- E is Evaporation
- Rs is Solar radiation
- Ta is Atmospheric Temperature
- Ra is Extraterrestrial Radiation
- RH is Relative Humidity

3.4.3.3.2 Evapotranspiration from the land surface

Evapotranspiration from the land surface was estimated using the Penman-Monteith Equation produced by the FAO Natural Resources Management and Environment Department. The derivation of estimates for the various parameters used in computing evapotranspiration were done following procedures outlined in the FAO Evapotranspiration Document (http://www.fao.org/docrep/x0490e/x0490e04.htm#TopOfPage) given as:

$$ET = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{Ta+273}U2(Es-Ea)}{\Delta+\gamma(1+0.34U2)}$$

Where

- ET is the reference evapotranspiration [mm day^{-1}],
- Rn is the net radiation at the crop surface [MJ m^{-2} day^{-1}],
- G is the soil heat flux density [MJ m^{-2} day^{-1}],
- Ta is the mean daily air temperature at 2 m height [°C],
- U2 is the wind speed at 2 m height [ms^{-1}],
- Es is the saturation vapour pressure [kPa],
- Ea is the actual vapour pressure [kPa],
- Es-Ea is the saturation vapour pressure deficit [kPa],
- Δ is the slope vapour pressure curve [kPa $°C^{-1}$],
- γ is the psychrometric constant [kPa $°C^{-1}$].

The estimates obtained were on a daily basis. These were then multiply by the respective surface areas as well as number of days in each month to obtain monthly estimates.

3.4.3.4 Water abstraction estimation

According to the CIA World Fact Book (https://www.cia.gov/library/publications/the-worldfactbook/fields/2202.html), the per capita annual freshwater withdrawal for Ghana as of 2000 is 48.82 m^3/yr. This value was converted into cubic millimetres per year and divided by 12 to obtain the per capita monthly freshwater withdrawal from the lake. Using the population map of communities around the lake's catchment area as produced by CERSGIS for the Man and Biosphere (MAB) Project (carried out by the Environmental Protection Agency), the total population of the communities around the lake as of the year 1984 was estimated to be about 6,000. Population growth rate is pegged at 3 per cent per annum (Ghana Statistical Service, 2010). With the assumption that growth rate had been fairly constant over the years, the value was then divided by 12 to obtain monthly growth rates. With the rate of change in population over the years considered, the population is then multiplied by the monthly withdrawal per capita to estimate the amount of water abstracted for domestic and agricultural purposes.

3.4.4 Sensitivity Analysis

The sensitivity analysis was carried out by changing an input variable in measures of a single unit, whiles keeping the others at their baseline values to determine the outputs. Afterwards, the variable was returned to its nominal value, then the process is repeated for each of the other inputs in the same way.

3.4.5 Calibration and Validation

The field data for the period of 1984-1998 was foremost screened to ensure that the data was sound (stationary, consistent and homogenous). These statistics were carried out using XLStat statistical software for Microsoft Excel. Afterwards, the Klemes (1986) split sample test method was employed in splitting the whole data into two sets: the first set - used in calibration and the second –validation. Calibration was done by soundly fine-tuning the models physical and numerical parameters using a trial and error approach to minimize the difference between model results and field observations. The modelled and field observations were then subjected to non-parametric regression to determine the coefficient of regression (R^2). This was done to determine how well the observed data is explained by the simulated. When an appropriate value for R^2 was obtained, the second independent data was used to validate the data without adjusting the models physical and numerical parameters.

3.4.6 Scenarios Data generation

Considering that there is currently an ongoing development of climate models for Africa, it was not possible to use weather generators to generate future synthetic weather scenarios for Lake Bosomtwe's locality as is the practice in other continents. In view of this shortcoming, the scenarios developed were based on statistical changes in observed data for the various parameters. For a degree rise in temperature, a unit of one degree was added to the entire temperature data to augment its average by one degree. A similar thing was also done for the rainfall data and the model run to determine outputs. Landuse(s) scenarios were also generated using 1986 data as baseline as given by Amo-Boateng (2011) in order to determine the impact of landuse changes on the lake water level. Since various land use(s) identified had different rates of change, the scenarios developed involved the entire conversion of a particular land use to another whiles holding all other variables (including other land uses) constant and running the model to produce outputs.

CHAPTER 4 SUMMARY OF KEY FINDINGS

4.1 Dominant water balance factors of Lake Bosomtwe

After a thorough review of existing literature on the subject matter, the following variables were identified as possible factor(s) or drivers of change affecting the water balance of rivers and lakes. They include precipitation (rainfall), evapotranspiration, surface water discharge, surface run-off from the catchment area, sub-surface runoff, regional groundwater contribution, water abstraction or withdrawal and seepage losses.

However, in the case of Lake Bosomtwe, a number of these factors presented above are ruled out on the basis of the following grounds:

i. It has been indicated the lake has a hydrologically closed basin (Turner *et al.*, 1996) thus eliminating the possibility of surface water discharge into other systems such as rivers etcetera.

ii. Subsurface runoff contributions to the lake is assumed to be negligible because of the steepness of the catchment which reduces infiltration and storage time on the catchment. Moreover, there is no existing data on the quantification of subsurface runoff contribution (Amo–Boateng, 2011).

iii. Groundwater contribution from the regional aquifer and seepage losses are minimal and thus eliminated on the basis that:

    a. The minimum elevation in water table in the plain surrounding the lake is 200masl (Gill,1969) which is several hundred meters above the current lake level, suggesting that the regional aquifer and the lake are hydrologically unconnected and that makes it impossible for water to seep out of the lake

b. Ground water seepage from the regional aquifer is also inhibited by the raised crater rim of the lake which induces a groundwater divide that inhibits subsurface flow from beyond the topographic divide (Turner *et al.*, 1996)

c. The lake lies in an impact amalgamated bedrock which should require outflow to occur within a slow fracture flow, however, 20m – 1000m thick of mud underlies the bottom of the lake (Turner *et al.*, 1996), hydraulically isolating the lake from any fractures in the bedrock.

In respect of grounds above, the following are the dominant factors that affect the water balance of Lake Bosomtwe. They include: rainfall, surface runoff, evaporation from the lake surface and water abstraction.

4.2 Catchment area of Lake Bosomtwe

The total catchment area (including the lake) is about 103.79 km^2 with a perimeter of about 59.71 km. The total lake surface area is estimated to be about 48.84 km^2 whereas the actual catchment area is about 57.94 km^2 (see Table 4.1).

Table 4. 1. The catchment area of Lake Bosomtwe (source: Amo-Boateng 2011)

Description	Area (km^2)	Perimeter (km)
Total Catchment area (including lake)	103.79019	59.71579
Total Lake Surface Area	48.84288	29.57527

Actual Catchment Area	57.94731	89.29106

4.3 Soil type

The soil types identified within the catchment area according to Amo-Boateng (2011) are Acrisols (Soil Group A) and Alisols (Soil Group B). Looking at the delineated catchment area of the lake, Acrisols occupy only the south-eastern portion. What is left thereof is occupied by the Alisols soil group (Figure 4.1)

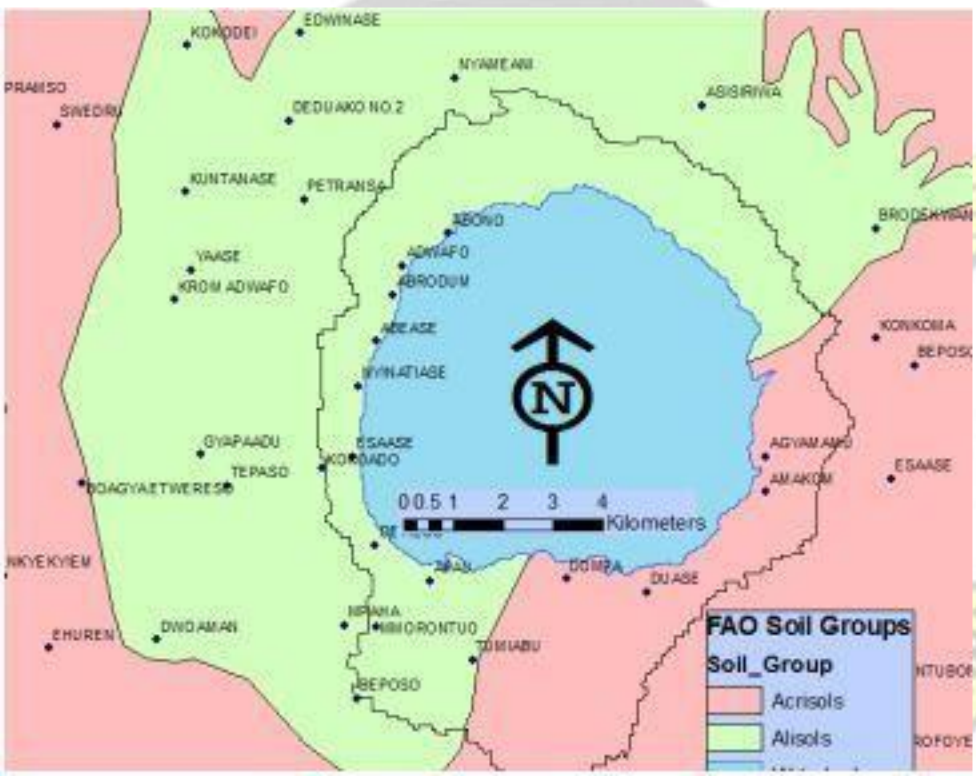


Figure 4. 1. Distribution of Alisols and Acrisols within the catchment area of Lake Bosomtwe (Source: Amo-Boateng, 2011)

4.4 Landuse and CN values of Lake Bosomtwe's catchment area

A total of five land use categories together with their area of coverage were identified on both soil groups (A and B) for the periods of December 1986 and May 2007. They included "closed forest", "open forest", "open area grassland", "shrubs and trees" and "settlement urban area". Whereas CN values generated remained the same, a comparison between land use/land cover categories for the aforementioned periods revealed that, the major land use change was the conversion of a large chunks of land mass delineated as "closed forest" to "open forest" in both soil groups. Refer to Table 4.2 for further details.

Table 4. 2. Land use/ land cover classifications of the Bosomtwe area for December 1986 and May 2007 (source: Amo-Boateng 2011)

Soil Group	Land cover Dec-86	Area (m^2)	CN Value	Soil Group	Land Cover May-07	Area	CN value	Change in area of land cover
	Closed forest	12,615,968.95	58		Closed Forests	1,310,289.33	58	-11,305,679.62
	Open Area / grassland	4,419,554.74	69		Open Area / Grassland	2,675,590.88	69	-1,743,963.86
B	Open Forest	3,841,926.22	65	B	Open Forests	11,447,649.47	65	7,605,723.25
	Settlement / Urban area	428,964.20	85		Settlement/ Urban Area	1,604,891.24	85	1,175,927.04
	Shrubs and trees	9,952,387.98	61		Shrubs / Trees	14,333,310.09	61	4,380,922.11
	Total Area	**31,258,802.09**			**Total Area**	**31,371,731.01**		
	Closed forest	17,432,782.69	32		Closed Forests	3,755,356.16	32	-13,677,426.53
	Open Area / grassland	1,255,543.19	49		Open Area / Grassland	1,135,094.30	49	-120,448.89
A	Open Forest	1,748,165.35	44	A	Open Forests	13,781,232.89	44	12,033,067.54
	Settlement / Urban area	145,800.00	77		Settlement / Urban Area	536,042.34	77	390,242.34
	Shrubs and trees	2,932,673.77	39		Shrubs / Trees	4,200,969.59	39	1,268,295.82
	Total Area	**23,514,965.00**			**Total Area**	**23,408,695.28**		

4.5 Estimation of water balance components

4.5.1 Rainfall

The monthly rainfall curve from the period of January 1984 to December 2013 is shown in Figure 4.2. The highest peak of 534.5 mm occurred in the month of September 2007. This was followed by a peak of 417.1 mm recorded in the month of July 1985. On a general basis, Kumasi experiences weakly bimodal rainfall pattern (Appendix 2). The first rainy season starts from a comparatively dry period in January having an average rainfall of 18.9 mm and peaks in June with an average rainfall of 211.7 mm. The second rainy season commences in August with an average of 87.7 mm, attains an average of 168.9 mm in September and drops to 26.4 mm in December. Running the standard normal homogeneity test and obtaining a p-value which was greater than the significance level (alpha=0.05) suggests that, the data used in this study is homogeneous (Appendix 3). On the whole, average monthly rainfall for the entire period is estimated at about 112.74 mm (Table 4.3).

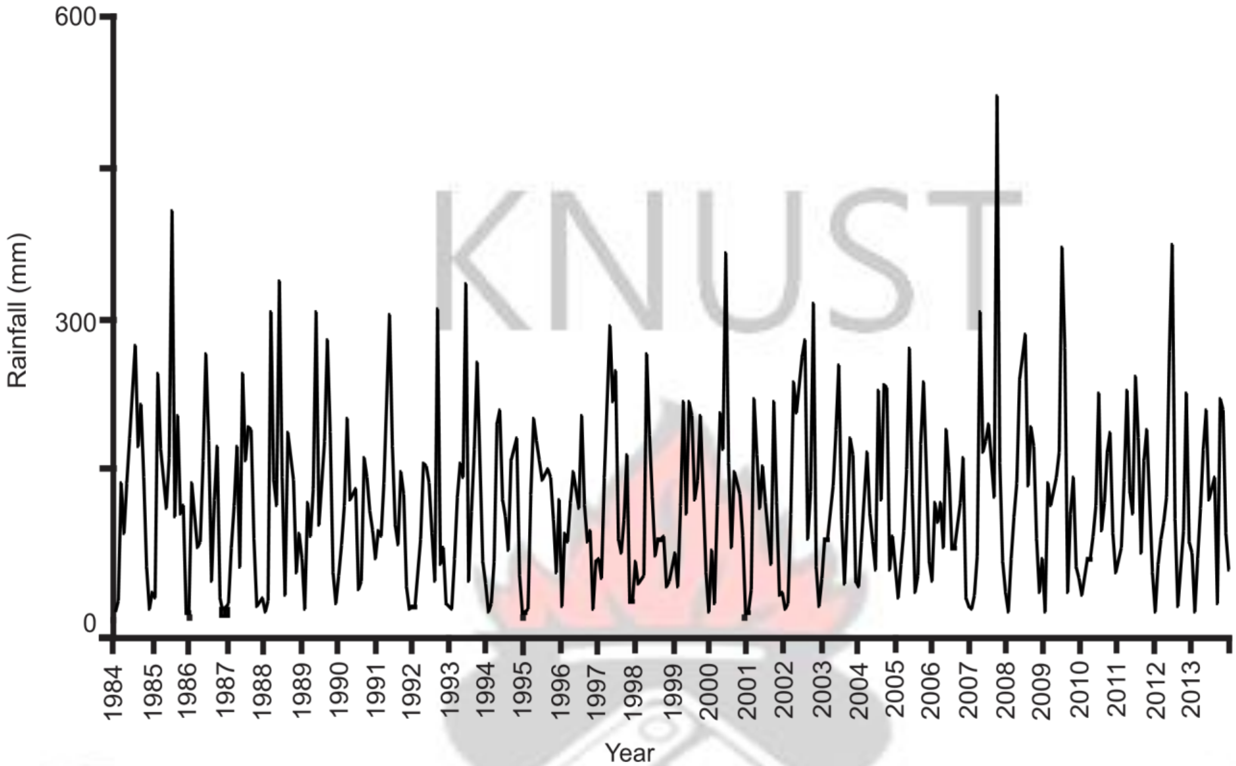


Figure 4. 2. Yearly rainfall plot for Kumasi from the period of January 1984 to December 2013

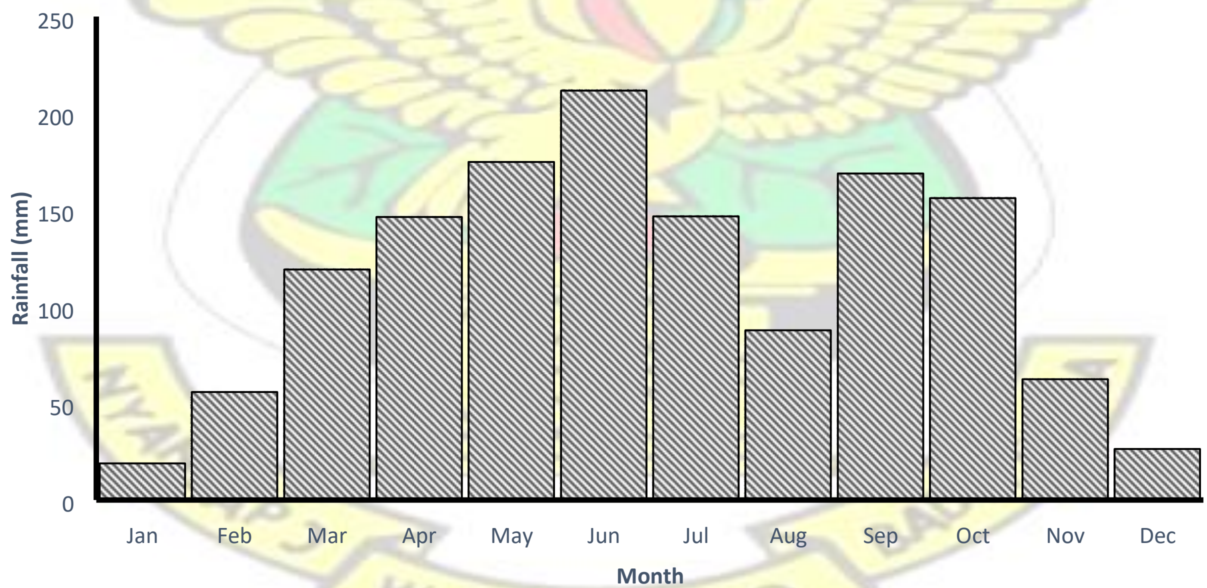


Figure 4. 3. Average monthly rainfall for Kumasi within a typical year

4.5.2 Surface Runoff

The trend of runoff estimates typifies that of rainfall. From the plot of surface runoff (as shown in Figure 4.4), Alisols generate more runoff into the lake than that of Acrisols.

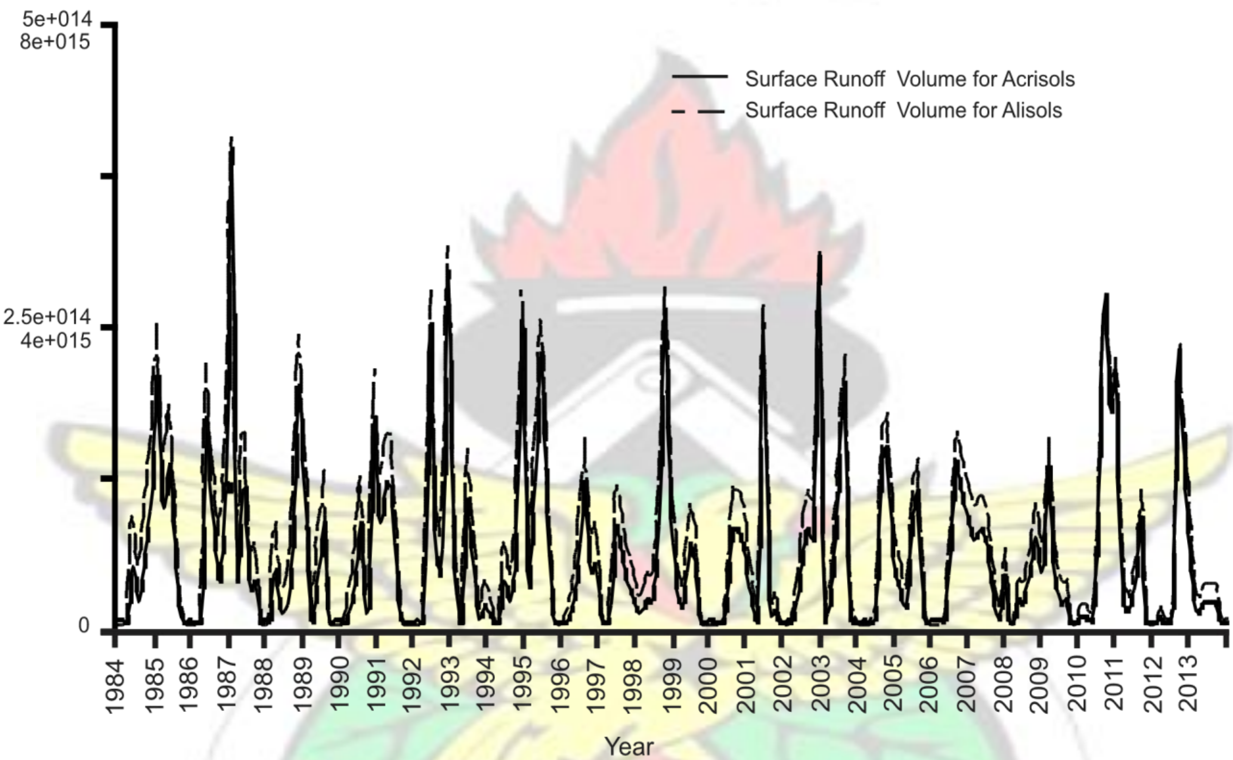


Figure 4. 4. Computed surface runoff estimates for Acrisols and Alisols within the catchment area of Lake Bosomtwe from the period of January 1984 to December 2013.

4.5.3 Evapotranspiration

The major parameters that were directly obtained from the field and used in estimating evapotranspiration were temperature and relative humidity. From Appendix 4, the maximum temperature recorded was 30.4 ºC whiles the minimum temperature observed was 23.9 ºC. Taking the average of the entire temperature data set, the mean temperature recorded from January 1984 to December 2013 is about 26.7 ºC. Average relative humidity (Appendix 6) also recorded was about 77.8, with a maximum of 90 as well as a minimum of 42. Running the standard normal homogeneity test for temperature as shown in Table 4.6 suggested that the temperature data set for the aforementioned period was homogeneous. However that of relative humidity was on the contrary (Appendix 7).

The monthly simulated evaporation from the lake surface is shown in Figure 4.5. The highest peak of about 177.53 mm/month occurred in February 2000. This is followed by January 2008 and January 2013 recording 177.09 mm/month and 169.23 mm/month in that order. As observed in Figure 4.6, evaporation from the lake surface are generally highest in March with an average of 169.8 mm/month and lowest in August with an average of 106.2 mm/month.

Similarly, the simulated evapotranspiration from the land surface is also shown in Figure 4.7. The highest peak of about 78.35 mm/month occurred in January 1984. This is followed by February 2000 and January 2008 recording 76.04 mm/month and 71.31 mm/month in that respective order. As shown in Figure 4.8, evapotranspiration estimates are generally highest in the month of March with an average of 71.50 mm/month and lowest in the month of August with 40.52 mm/month as an average.

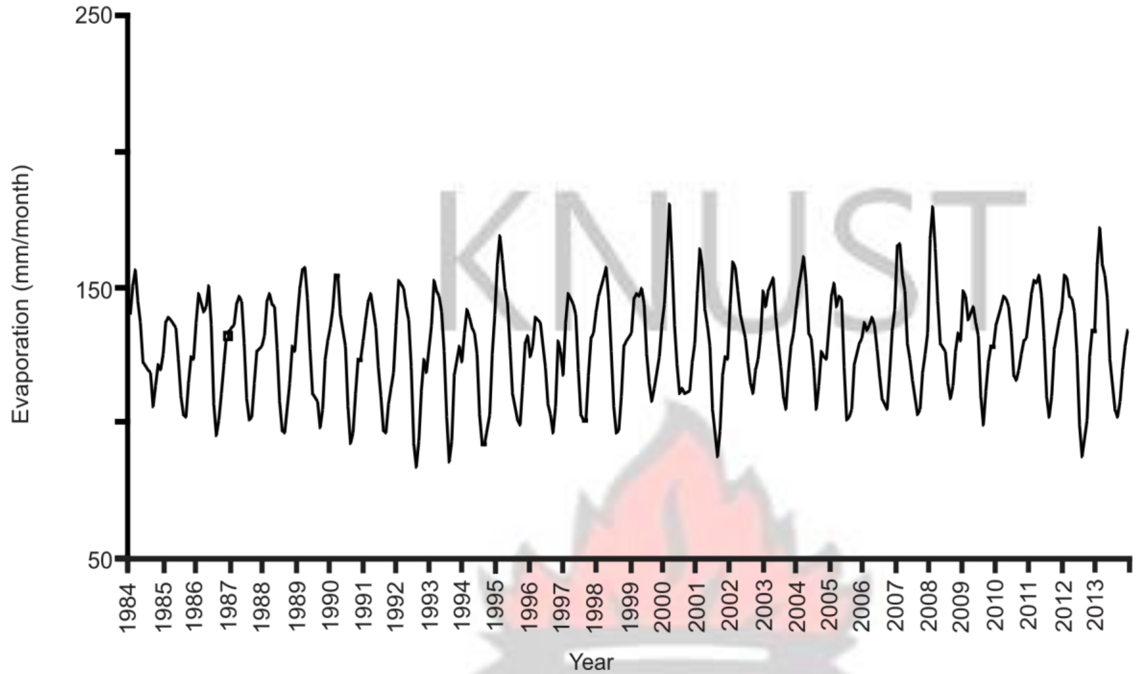


Figure 4. 5. Monthly estimated evaporation from the surface of Lake Bosomtwe over the period of January 1984 to December 2013

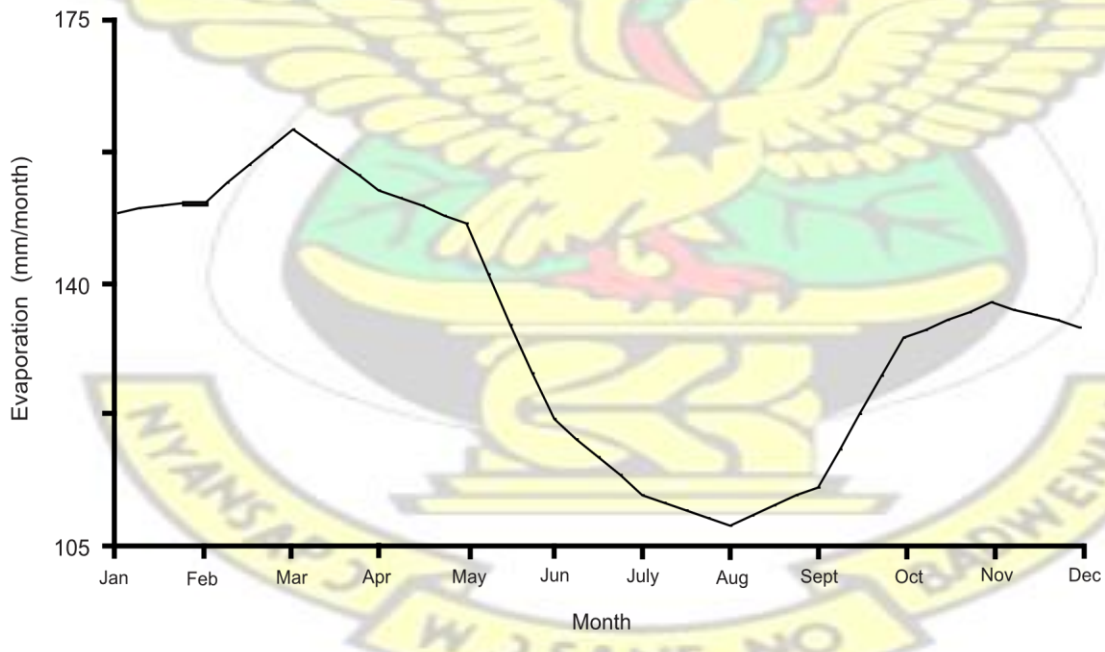


Figure 4. 6. The average monthly evaporation estimates of Lake Bosomtwe within a typical year.

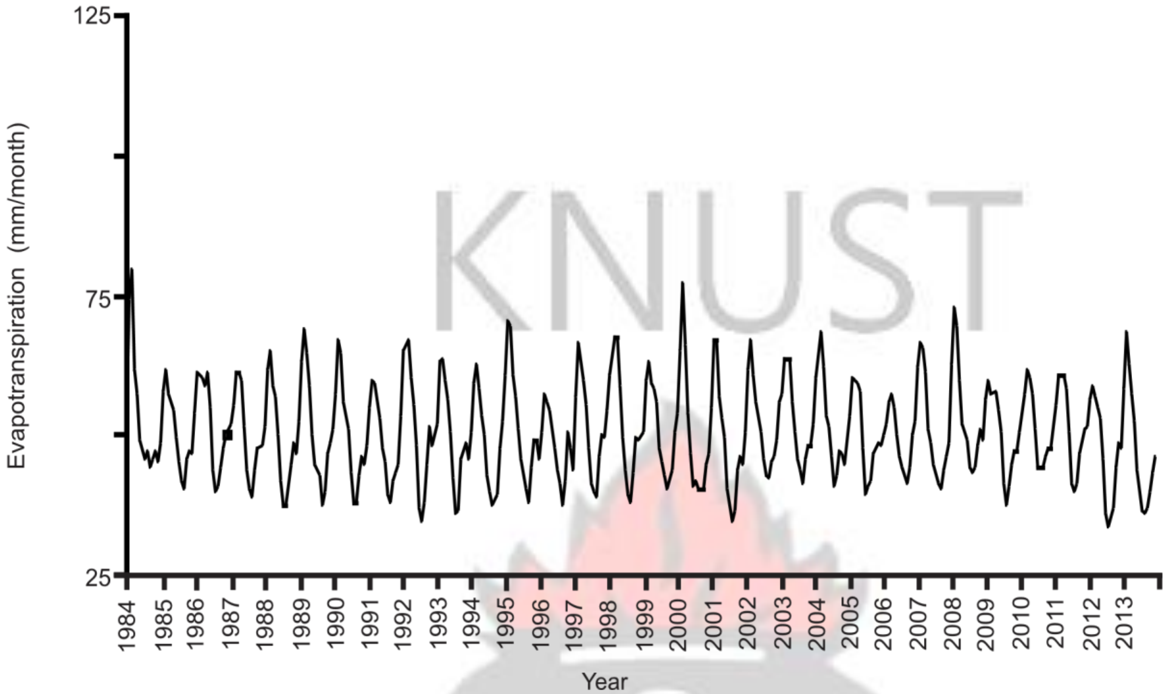


Figure 4. 7. Monthly estimated evapotranspiration from the land surface around Lake Bosomtwe over the period of January 1984 to December 2013.

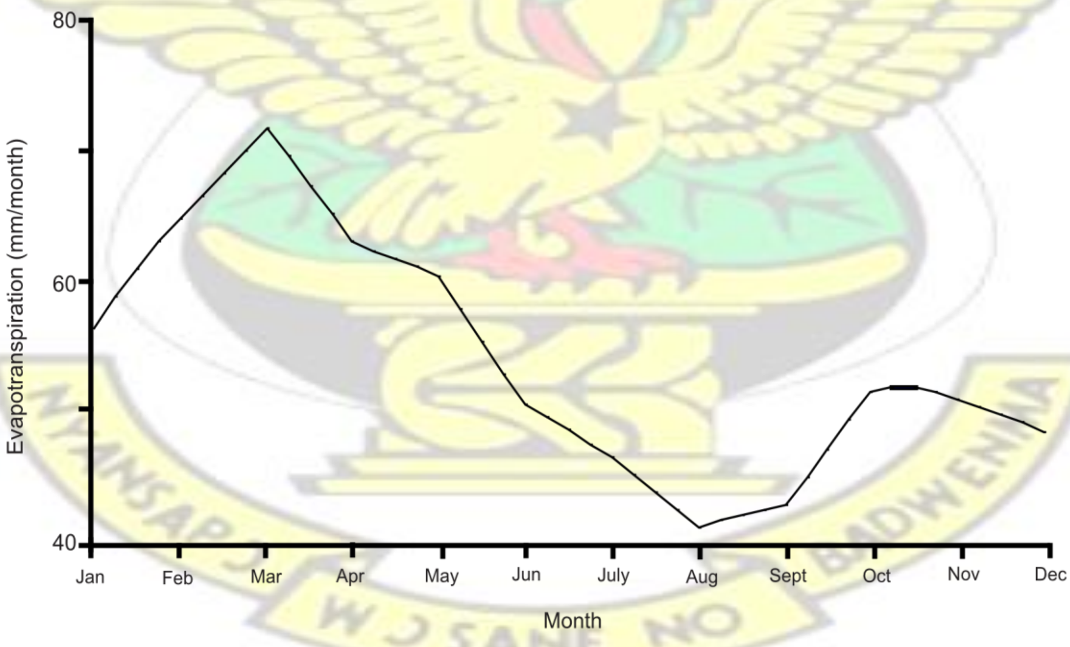


Figure 4. 8. The average monthly evapotranspiration estimates within a typical year.

4.5.4 Water withdrawal

Figure 4.9 shows an exponential growth in water abstraction from about 24,030.025 m^3 in January 1984 to about 58,809.540 m^3 in December 2013.

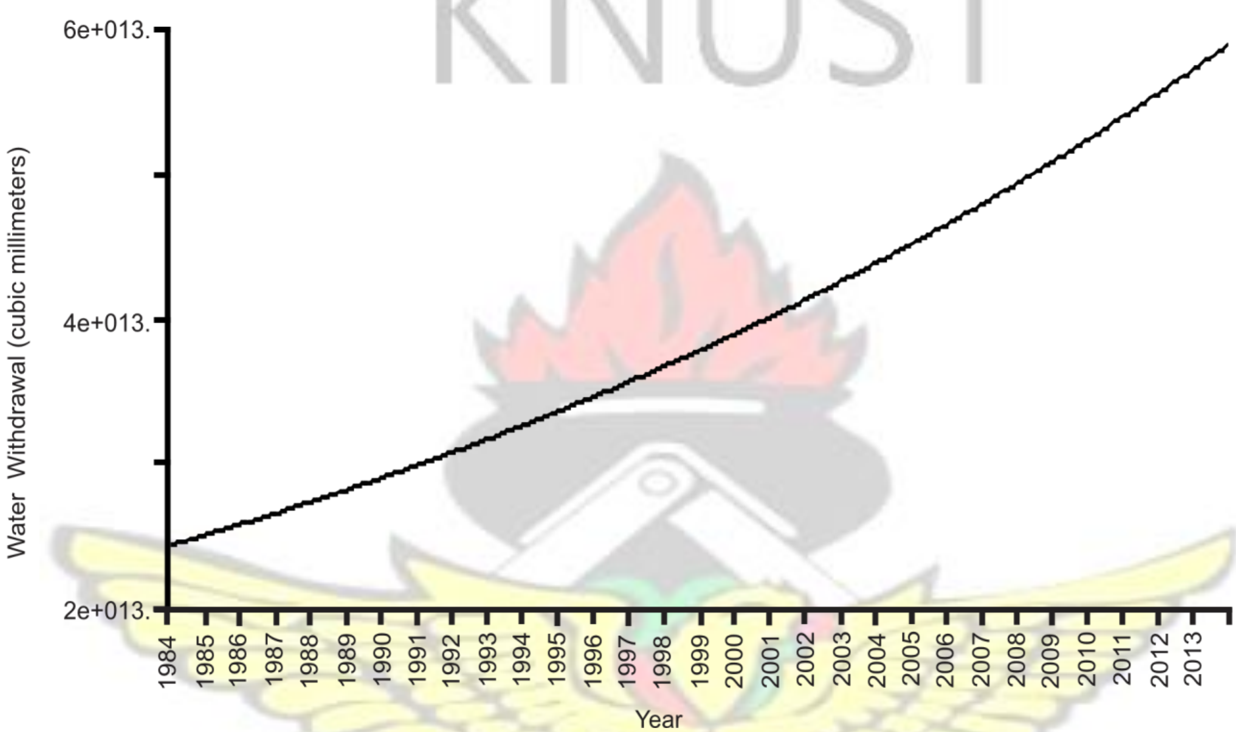


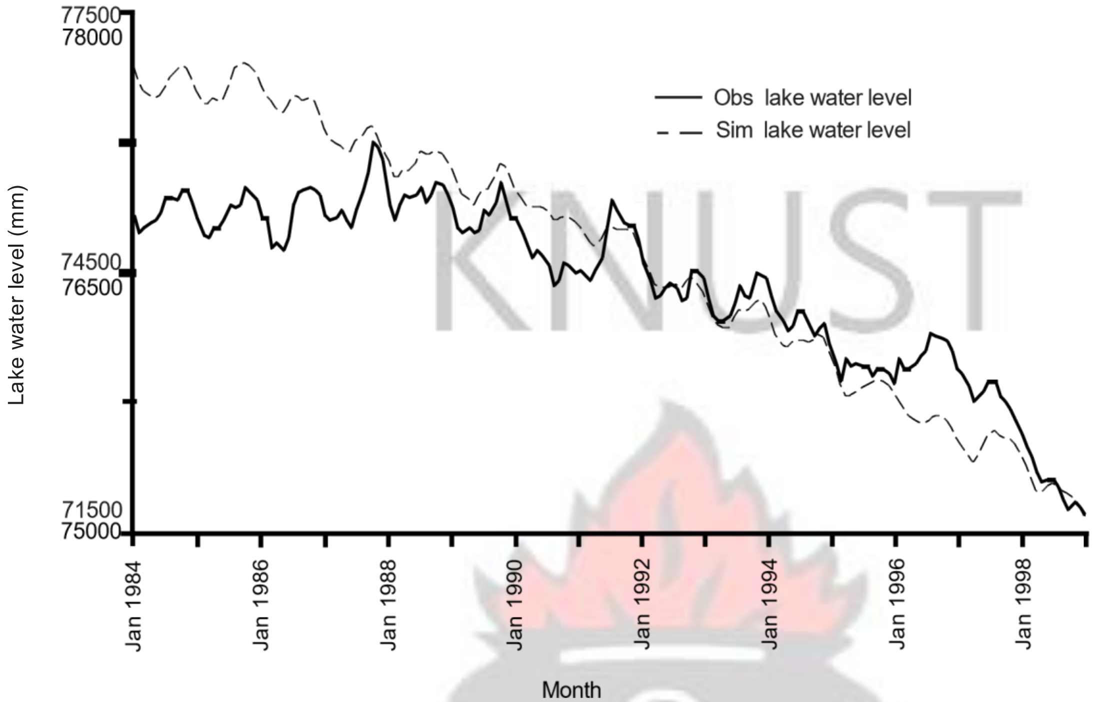
Figure 4. 9. Yearly water withdrawal from Lake Bosomtwe over the period of 1984 to 2013

4.6 Calibration of simulated lake water level

4.6.1 Graphical Results

The simulated lake water level before and after the model was calibrated are shown in Figure 4.10a and b. Introducing the constants $K_{factor} = 0.87$ and $L_{factor} = 0.87$ into the evaporation and evapotranspiration equations respectively as well as employing the non-parametric regression, the co-efficient of determination (R^2) was calculated and found to be 0.93. The model's efficiency (Nash and Sutcliff) was also calculated and found to 82.43%. Comparing the simulated and observed data sets, it was found that the observed data has a maximum of 77,240 mm and a minimum of 75,080 mm whereas the simulated data has a maximum of 77,266 mm and a minimum of 75,026 mm (Table 4.3).

a)



b)

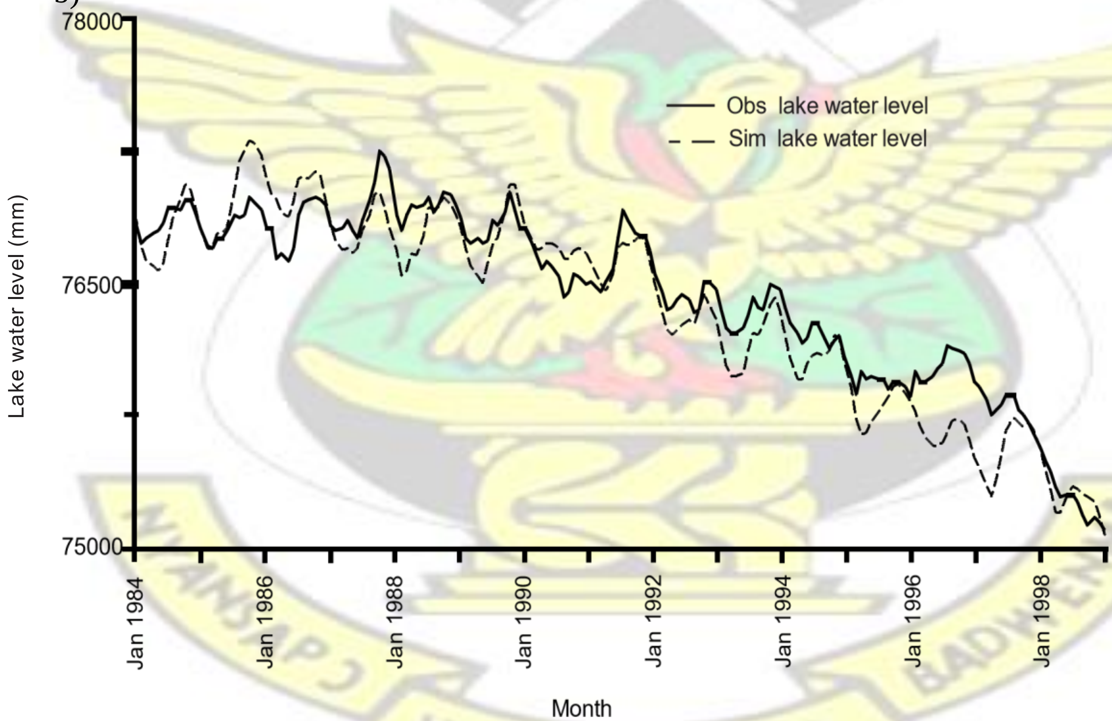


Figure 4. 10. Lake Bosomtwe's water level dynamics before (a) and after (b) calibration during the period of 19841998.

4.6.2 Statistical Results

Table 4. 3. Nonparametric regression of variable Simulated:

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Simulated	160	0	160	75026.8	77266.1	76304.3	574.544
Observed	160	0	160	75080	77240	76414.4	497.867

Table 4. 4. Goodness of fit statistics

R^2	0.9316
SSE	3591926
MSE	22449.5
RMSE	149.832

4.7 Scenarios

4.7.1 Baseline

Amidst the fluctuations (noise) as shown in Figure 4.12, the water level gradually rose from 76,820 mm in January 1984 to 77,047.84 mm in January 1986 and then declined steadily to about 73,675.70 mm in March 2007 where there is a notable sharp decline. This is followed by an immediate ascent from 73,724.77 mm in April 2007 to 74,538.30 mm in October 2008. From then onwards, the water level fluctuates with a relatively less steep descent (declining slope) to 74,079.98 mm in December 2013.

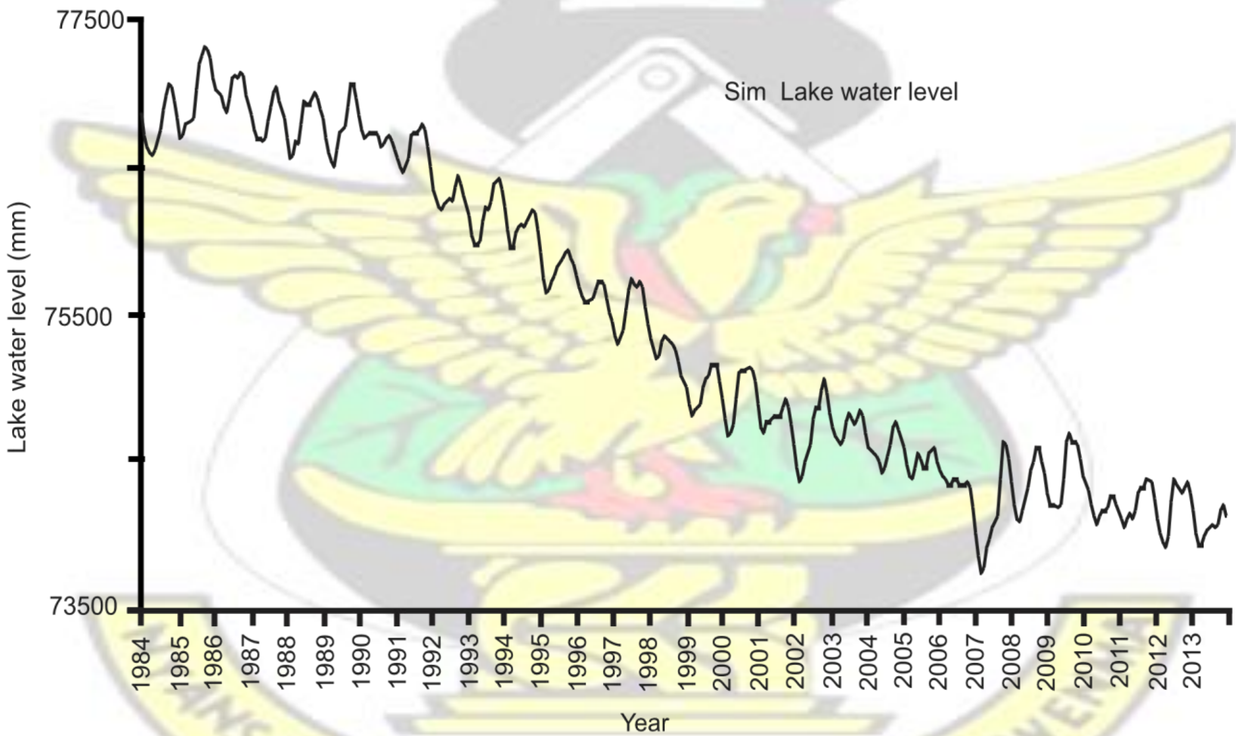


Figure 4. 11. Lake Bosomtwe's baseline water level dynamics from the period of 1984 to 2013

4.7.2 Climate Scenarios

4.7.2.1 Temperature trend and scenarios

Figure 4.13 shows the average monthly temperature for Kumasi over the period of 1961 to 2013. It is observed that the temperature for Kumasi increased significantly (Z = 7.44, Q = 0.0279) over the time frame and is likely to progressively increase as a consequence of climate change. Relating the impact of increasing average temperature on the lake water level dynamics. The lake water balance scenarios with statistical unit increments in temperature over the period of January 1984 to December 2013 when all other factors are held constant is represented in Figure 4.14. Generally, the fluctuations and therefore the behaviour along the descents in the three scenarios are the same except that the slopes along which the descents are taking place vary markedly. Whiles scenario 1 (no change in average temperature) starts from 76,820 mm and ends at 74,384.50 mm scenario 2 (a degree rise in average temperature) and 3 (2 degree rise in average temperature) start from 76,820 mm and end at 73,546.25 mm and 72,716.75 mm respectively.

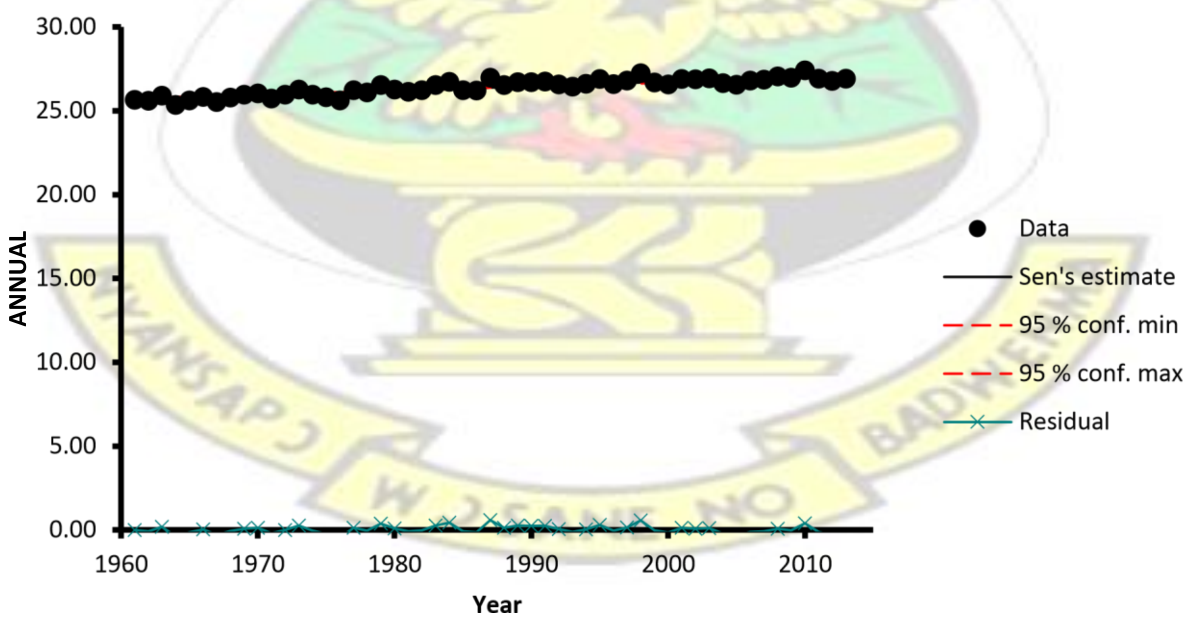


Figure 4. 12. Average monthly temperature from the period of 1961 to 2013

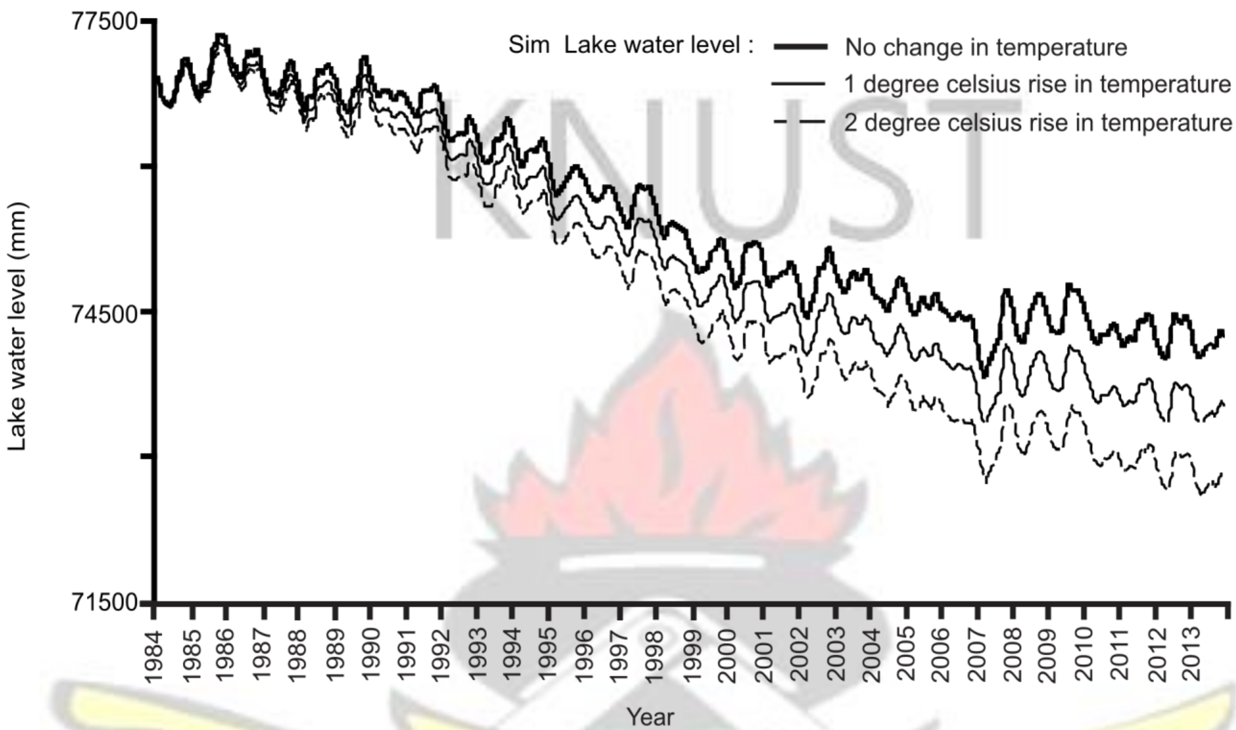


Figure 4. 13. Lake Bosomtwe water balance scenarios with statistical unit increments in temperature.

4.7.2.2 Rainfall trend and scenarios

There was a relatively minute, progressive and non-significant decreasing trend in the amount of rainfall (Z = -0.41, Q= -0.741) in Kumasi from the period of 1961 to 2013 (Figure 4.15). Having established this, the scenarios in Figure 4.16 therefore focus on statistical unit increments in amount of rainfall over the period January 1984 to December 2013 holding all other factors constant. As observed in the temperature scenarios, the fluctuations and therefore the behaviour along the descents in the three scenarios are the same except that the slopes along which the descents are taking place vary notably. Whiles scenario 1 (no change in rainfall) decreases from 76,820 mm to 74,079.98 mm in December 2013, scenario 2 (a millimetre increase in average rainfall) and 3 (2 millimetre increase in average rainfall) decrease from 76,820 mm to 74,486.30 mm and 74,868.25 respectively.

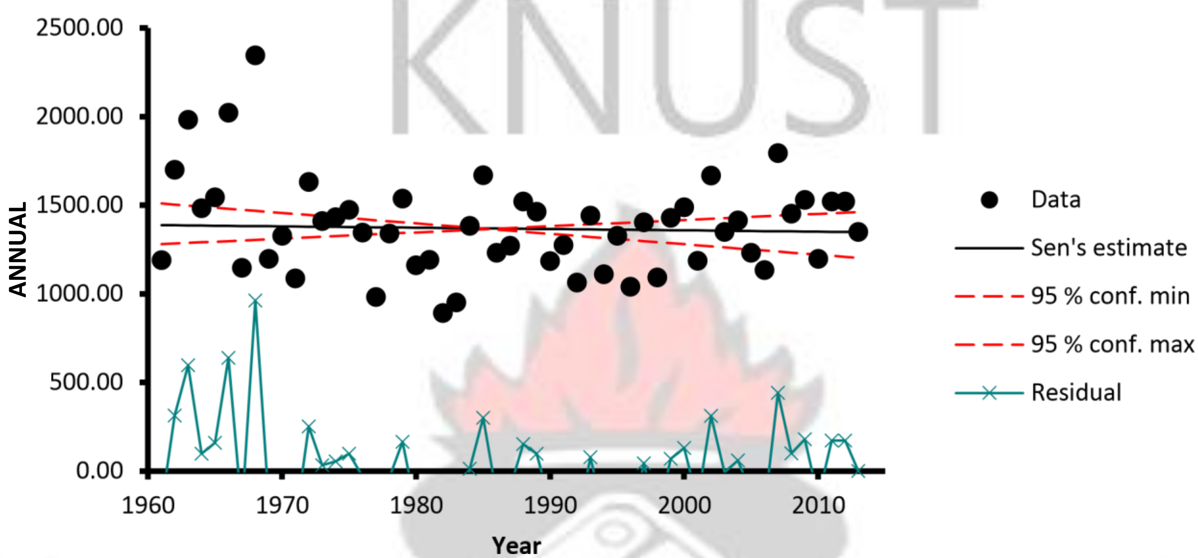


Figure 4. 14. Annual rainfall trend for Kumasi from 1960 - 2013

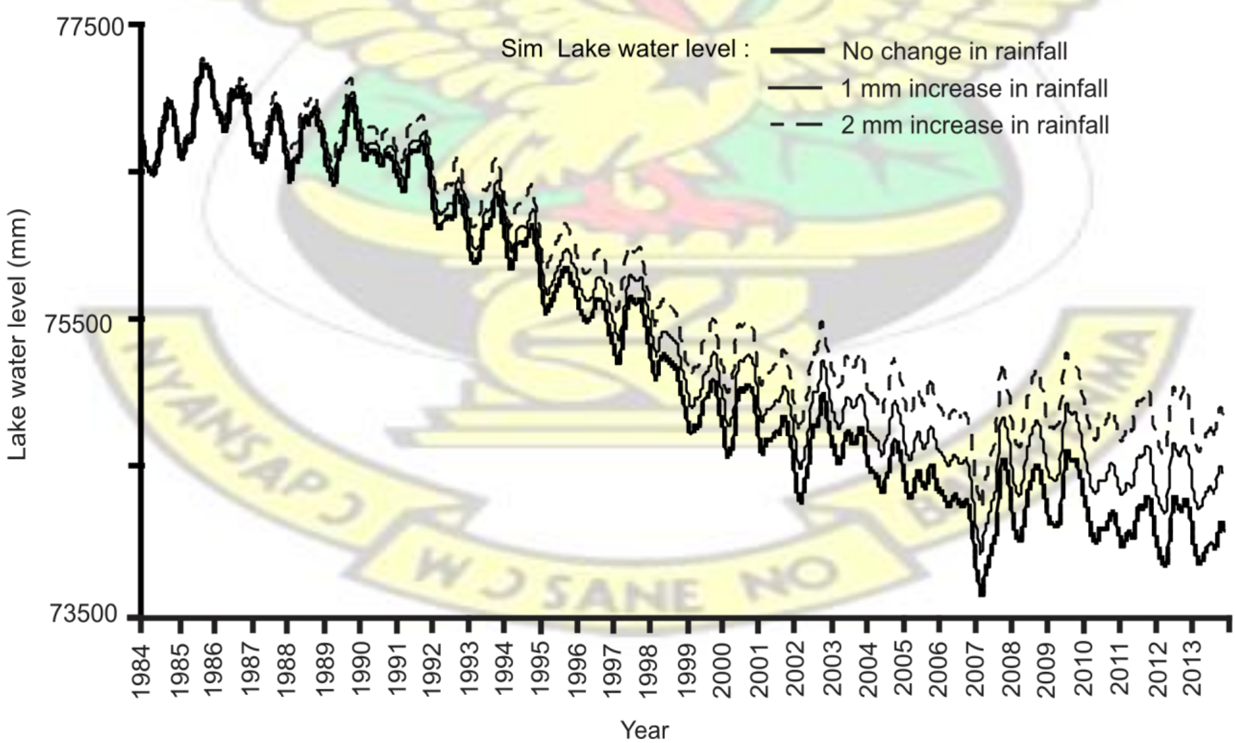


Figure 4. 15. Lake Bosomtwe water balance scenario with a statistical unit increments in rainfall.

4.7.3 Land use scenarios

4.7.3.1 Closed forest to open forest

Figure 4.17 shows a comparison of scenarios in which a “closed forest” which is converted into an “open forest” is compared to the baseline scenario. As observed, water levels for the two scenarios start out initially as the same (76,820 mm) until January 1990 where there was a progressive marked increment in the water level for the “closed to open forest” scenario even though both scenarios exhibit the same behaviour. Lake water levels obtained at the end of the simulations for the scenarios place the “closed to open forest” scenario at 74,184.68 mm whereas the “baseline” scenario is at 74,079.98 mm.

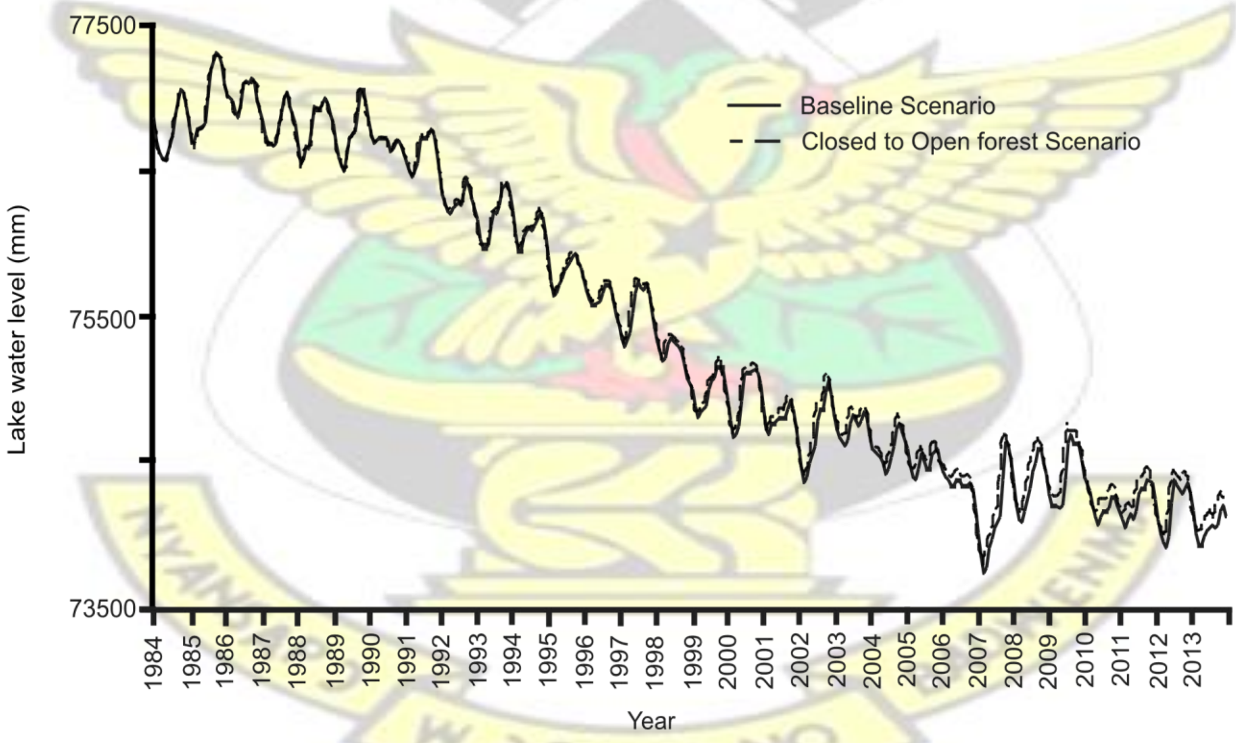


Figure 4. 16. Lake Bosomtwe water balance scenario in which there is a total conversion of closed forest to open forest

4.7.3.2 Closed forest to Settlement

A similar occurrence as observed in “closed forest conversion to open forest” happens in this scenario (Figure 4.18). The only difference is that the progressive increment observed in the “closed forest to settlement” scenario is more pronounced from January 1990 as compared to that of Figure 4.17 and thus constitute a significant change. At the end of the scenario simulations, the “closed forest to settlement” scenario is pegged at 74,340.66 mm whereas the “baseline” scenario is at 74,079.98 mm.

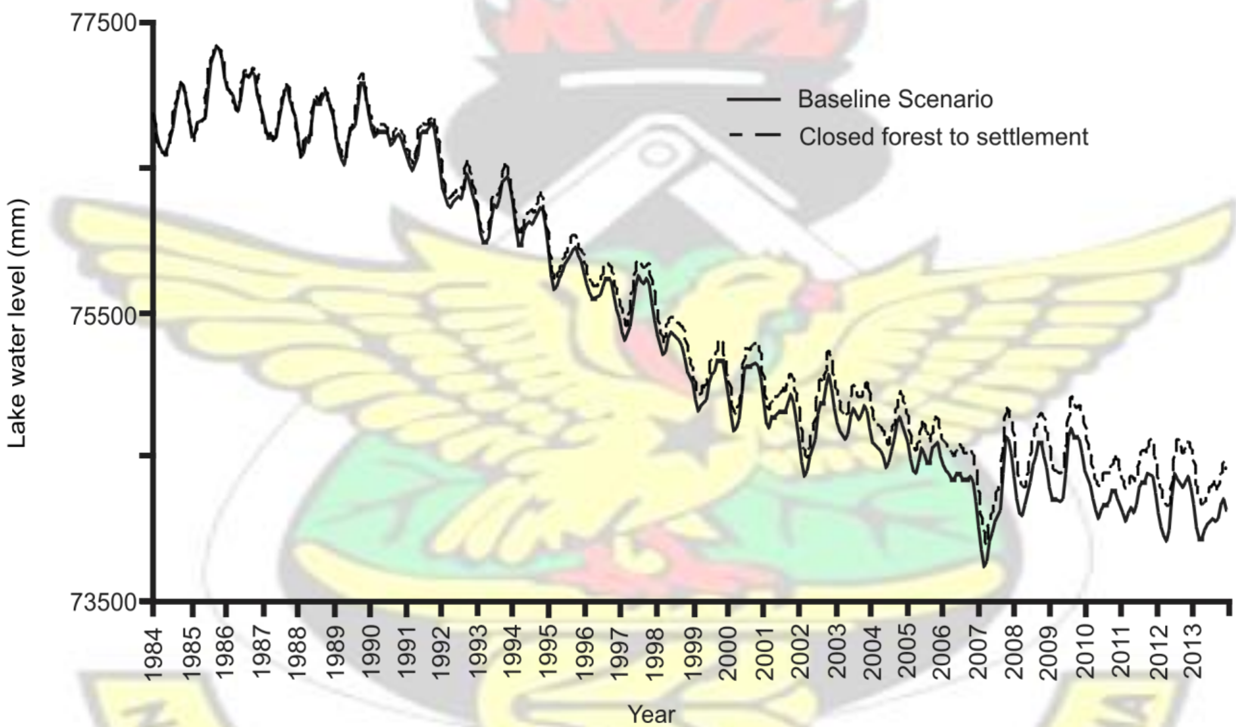


Figure 4. 17. Lake Bosomtwe water balance scenario in which there is a total conversion of the closed forest to a settlement.

4.7.3.3 Closed forest to Open grassland

The conversion to open grassland (Figure 4.19) is similar to other conversions described earlier (Figure 4.17 and Figure 4.18). From the period of January 1990 onwards, there is a progressive and marked increment in the water level for the “closed forest to open grassland” scenario in comparison to the baseline scenario. It must however be mentioned that increments in water levels are higher than that shown in Figure 4.17 but not as pronounced as in the case of Figure 4.18. Lake water levels obtained at the end of the simulations for the scenarios place the “closed forest to open grassland” scenario at 74,219.77 mm whereas the “baseline” scenario is pegged at 74,079.98 mm

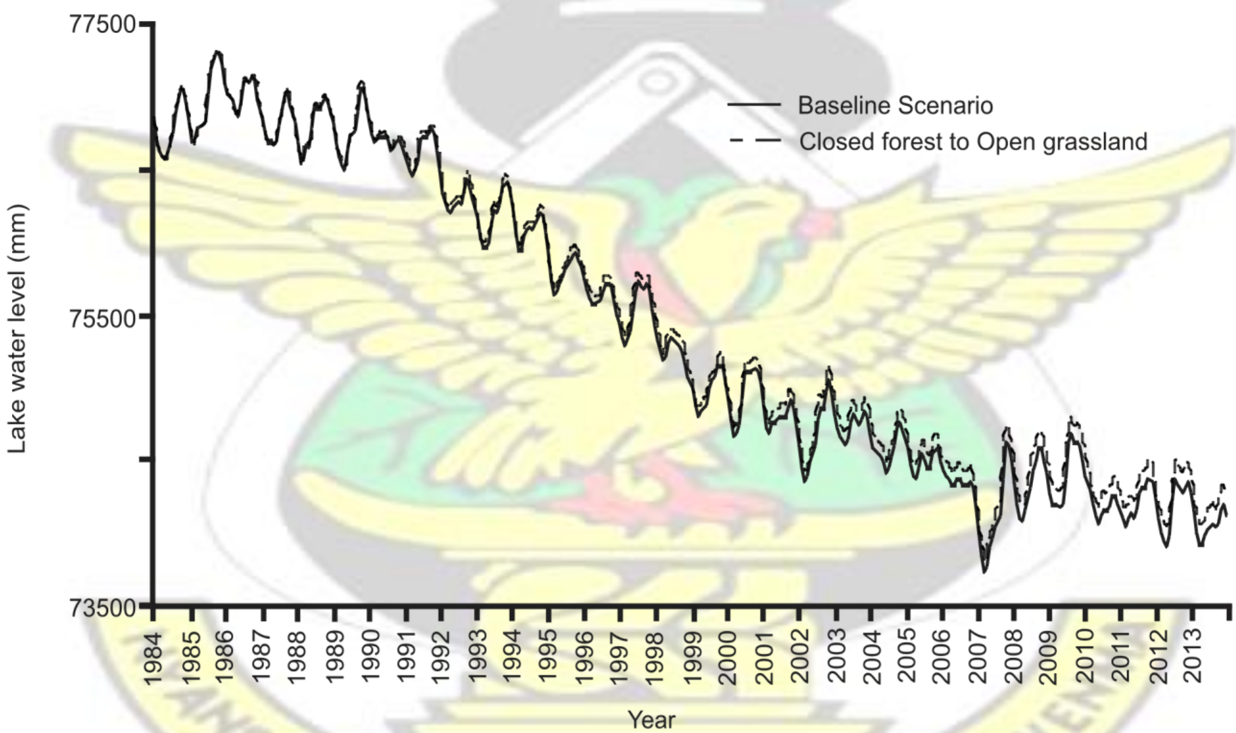


Figure 4. 18. Lake Bosomtwe water balance scenario in which there is a total conversion of closed forest to open grassland.

4.7.3.4 Shrubs and trees to Open grassland

Figure 4.20 compares the scenario in which "shrubs and trees" are converted into "open grassland" to the "baseline" scenario. In this case, water level dynamics for the two scenarios are about the same. At the end of the scenario simulation, the "shrubs and trees to open grassland" scenario records a water level of 74,101.98 mm whereas the baseline scenario records a level of 74,079.98 mm

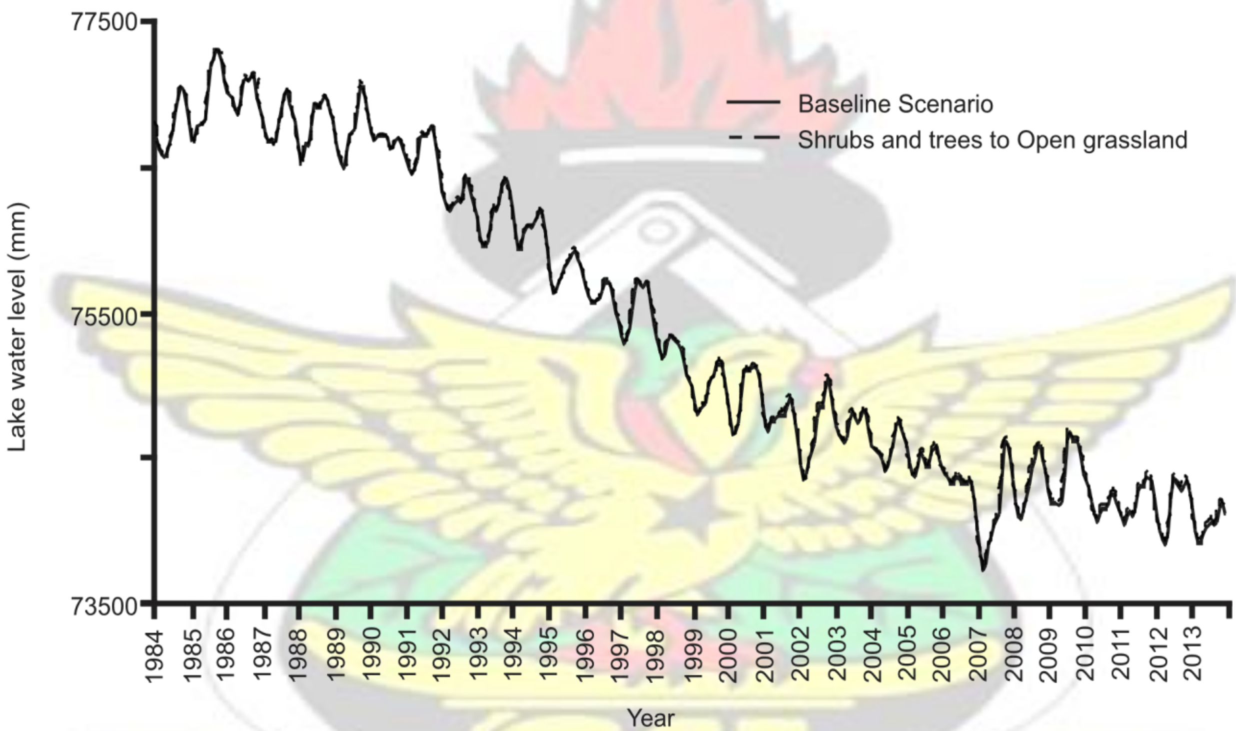


Figure 4. 19. Lake Bosomtwe water balance scenario in which there is a total conversion of shrubs and trees to open grassland.

4.7.3.5 Open grassland to Settlement

Figure 4.21 similarly compares the scenario in which "Open grassland" are converted into "settlement" to the "baseline" scenario. In this case too, water level dynamics for the two scenarios are about the same. At the end of the scenario simulation, the “open grassland to settlement” scenario records a water level of 74,094.24 mm whereas the baseline scenario records a level of 74,079.98 mm.

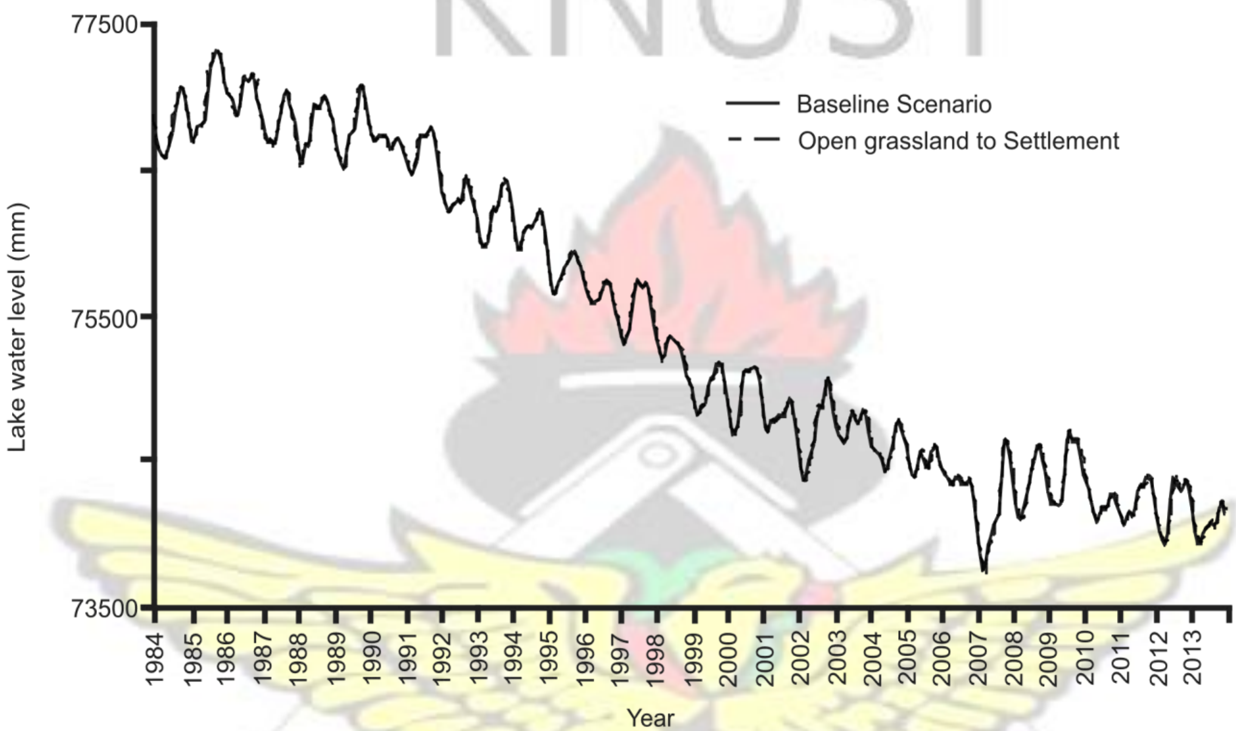


Figure 4. 20. Lake Bosomtwe water balance scenario in which there is a total conversion of open grassland to settlement

CHAPTER 5 DISCUSSION

5.1 Conceptual diagram and model

After careful review and consideration of all available literature on the lake's hydrology, the singly plausible conceptual diagram that could account for all conditions and catchment characteristics spelt out in all available literature on Lake Bosomtwe is that which is presented in the methodology. This conceptual diagram incorporates the argument of Turner *et al.* (1996) that, the lake is a hydrologically closed basin lake. In like manner, it supports the hydrological disconnection opinion of Gill (1969) between the regional aquifer and the lake since the minimum elevation in water table in the plain surrounding the lake's catchment (and not the lake) is 200masl and is several hundred meters above the current lake level. Turner *et al.* (1996) explains that the regional aquifer is inhibited by the raised crater rim of the lake which induces a groundwater divide that inhibits subsurface flow from beyond the topographic divide. Based on these arguments this study therefore proposes that, but for the spill way, the lake water level has the potential to rise to the tip of the seemingly mountainous region surrounding the lake catchment periphery. However, over a geological period of time, the lake water level has reduced to the current level as a consequence of both active climatic and anthropogenic forces. This theory is very much consistent with the meteoritic activity believed to have taken place during its formation.

Agreeing with Zhang *et al.* (2008) that catchment water balance is influenced by climatic factors as well as catchment characteristics, the conceptual model developed and employed in this study identifies rainfall, and for that matter, surface runoff as the main input sources of water into the lake whereas evaporation from the lake surface, evapotranspiration from vegetation and land surfaces as well as water abstraction remain the sources of water loss.

This conceptual model is therefore a build-up on that of the previous studies of Amo-Boateng (2011) and Turner *et al.* (1996). Rather than lumping all forms of water losses as a consequence of evaporation, the model developed out of this research separates the various forms of water losses and accounts for each. In addition, this model sharply contrasts the view held that water abstraction should be neglected as purported by Turner *et al.* (1996). This is because, the major sources of water for domestic purposes are predominantly boreholes and hand dug wells (Ghana Statistical Services, 2010) which have been sunk for use by communities within the lakes catchment area. Knowing that the regional aquifer and the lake are hydrologically disconnected, it imply that water obtained from boreholes and hand dug wells within the lakes catchment area are far more important than thought by the earlier authors.

5.2 Rainfall

The results for rainfall simulation indicates a high variability in rainfall amounts on a monthly basis over the period of 1984 to 2014. This is very much consistent with the generally accepted stochastic nature of rainfall records since variability in rainfall may be associated with the inconsistencies in its quantity and temporal distribution as suggested by Campion (2012). However analysing the rainfall data sets within a typical year time frame, Campion (2012) observed that the seasonal precipitation cycle over Ghana gradually advances from an all year round or a two distinct rainy seasons from the coastal areas to a single rainy season in the north.
Thus by virtue of the lake's location around latitude 6° N, a bimodal rainy seasons with a lower second peak is observed as shown in the results (Figure 4.3). Barbé *et al.* (2002), explained that the dominant rainfall formation mechanism in the region involves convection complying with the movements of the Intertropical Convergence Zone (ITCZ). From their observation, after September, the ITCZ recedes and there is less available moisture ladened winds to cause rainfall, hence the weaker second peak and the reduced water input into the lake.

5.3 Runoff

Simple methods for predicting runoff from watersheds have been reported by Abon *et al.* (2011), Steenhuis *et al.* (1995) and van Dijk, (2010) to be particularly useful in hydrologic engineering and hydrological modelling. Thus in this study, the SCS-CN method which is very simple to calculate is used in the simulation of surface runoff. It was employed by Amo-Boateng (2011) in estimating runoff into Lake Bosomtwi and the results obtained were satisfactory. From the simulation results obtained, the runoff curves for the two soil types (Alisols and Acrisols) mimicked that of rainfall and it was realized that Alisols generate more runoff than the Acrisols.

The general consensus among researchers is that the hortonian mechanism dominates the runoff generation process in the tropics whiles the dunnes mechanism applies to flood plains and valley bottoms (Esteves and Lapetite, 2003; Masiyandima *et al.*, 2003; Joel *et al.*, 2002; Peugeot *et al.*, 1997; Dunne, 1978). Having an irregular cone-shaped landscape, Amo-Boateng (2011) concurs that runoff drains along a slope into Lake Bosomtwe and argues that the steepness of the catchment reduces infiltration and storage time of runoff within the catchment before it gets into the lake. Consequently, one is inclined to concede to the view that, the runoff mechanism prevalent may be Hortonian in nature. However this stance is not absolute since Loague and Abrams (2001) have reported that due to spatial variability in rainfall and catchment characteristics, it is unlikely that larger basins produce runoff with just one mechanism. Simulations have shown that Hortonian and Dunne runoff processes can occur simultaneous at different locations or switch from one process to the other at the same location depending on initial conditions and characteristics of the rainfall event. Therefore the forested and agricultural areas are likely to support some amount of infiltration whereas the open areas and settlements are likely to encourage runoff into the lake

5.4 Evaporation and Evapotranspiration

According to Alkaeed *et al.* (2006), potential evapotranspiration can be measured directly. It must be mentioned that the technology of lysimeters, and for that matter, field data on evapotranspiration from the catchment (over the time period of 1984 to 2013) was not readily available as at the time this work was being carried. What was available was relatively scanty pan evaporation data which Amo-Boateng (2011) compared to a number of potential evaporation evapotranspiration models and concluded that a modified version of the standard Penman evaporation model by Valiantzas (2006) produced satisfactory results in estimating evaporation from the lake surface.

Since soil surfaces and vegetation lose water to the atmosphere by evapotranspiration, there was a need to account for that component. Thus, the Penman Monteith model which is universally accepted as the standard method for estimating potential evapotranspiration and to which other potential evapotranspiration models are compared (Allen *et al.*, 1998) was also incorporated into the conceptual model.

From the simulation results, both models produced similar behaviour (Figure 4.5 and Figure 4.7) except that the curve for evaporation from the lake surface had a higher magnitude as compared to that of the land surface. This is very much expected since more water was available for evaporation from the lake surface as compared to that of the land surface. The very similar behaviour of the two independent models indeed suggest that the estimates produced may be representative of the actual evapotranspiration emanating from the catchment.

5.5 Water abstraction

Prehistoric studies have shown that many ancient cities and communities have been cited near or around waterbodies. Classical examples include London on the River Thames and Paris on River Seine. The siting of such cities near or around rivers demonstrates how important water is to human sustenance and so it is not surprising to find about twenty four communities around the lake. Prakash *et al.* (2005), have clearly stated that the lake and its resources serve as the main source of subsistence for the indigenes. Therefore, having established that the boreholes and hand dug wells sunk within the communities (in the lake's catchment area) serve as the main source of water for domestic purposes imply that, ideally, an increase in population will result in a commensurate increase in water demand. This argument thus supports the observed exponential increment in water abstraction along the years as a consequence of population increase.

5.6 Simulation of lake water balance

The simulation approach to this work follows the conventional monthly lake water level estimation over a period of years (in this case from 1984-2013). This provides basis for assessing the lake water level behaviour on two levels: the behaviour of the lake within a typical time frame of a year as well as the behaviour of the lake between years. However in this case, the lake water level behaviour is limited to the latter.

The performance of the water balance model is evaluated by the comparison of simulated and observed lake water levels. The results suggest a small error variance in measured data as explained by the model (R^2 = 0.93) even though there is a "poor" fit in behaviour in certain portions. Some portions along the trajectory had simulated lake water levels significantly lower or higher than as observed. It is possible certain parameters and processes specific to the catchment setting may have been overestimated, underestimated or completely neglected in the model. The assumptions made to simplify the model as well as calculations could also be contributing factors. For instance, the uniform distribution assumption and transfer of meteorological parameters (rainfall, humidity and temperature) from Kumasi as representative of the Bosomtwe district could have erroneously overestimated or underestimated the model.

Generally, there are several possible sources of errors but are usually categorized under two main captions: namely, systematic and random errors. Random errors according to Topping (1972) are caused by unknown and unpredictable changes such as spatial and temporal complexities in environmental conditions and thus may not be easily accounted for. As a case in point, it is observed that, for the period of January 1996 to June 1996, the trend in behaviour between simulated and observed lake water levels are diametrical and then immediately return to normalcy afterwards. Systematic errors, on the other hand, hail from instruments (Topping, 1972). In this case, it is possible that some of the measuring instruments used in collecting field data could have been defective or were wrongly used in collecting data. Nonetheless, the moderately strong correlation between the observed and simulated lake water level may suggest a true mimicry of the system and therefore very little contribution of errors.

5.7 Climate scenarios

From the results it is clear that both "a statistical degree rise in temperature" and "a statistical millimetre rise in rainfall" do have significant impacts on water levels. While it graphically appears that "a degree rise in temperature" impacts more on the lake water level than "a millimetre rise in rainfall", establishing which of the two, the lake water level is more sensitive to, has been very difficult. This is because they are on different measurement scales, thus there is no basis for comparison. Despite this set back, Fedeski and Gwilliam (2007) reported that, however small it is, the change in climate (and therefore any of the climate parameters) could modify some elements of the water cycle such as soil moisture, groundwater recharge, evapotranspiration and runoff.

5.8 Land-use/land cover scenarios

There is a general consensus amongst scientist that land use has a strong influence on the water balance of a given area. Neelakantan and Remaya (2015) have reported that changes in land use / land cover affect runoff characteristics. The relationship lies particularly in the fact that different kinds of land uses / land cover allow different levels of rain water to infiltrate the ground. Whereas a vegetated land cover around the the lake will impede the rate of runoff, a built-up environment will result in less infiltration and increased runoff. Where there is a conversion from one form of vegetation cover to another, then the decided factor becomes the density of vegetation. Therefore the scenarios as observed in the results are very much consistent with literature.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study sought to contribute to the pool of knowledge on the hydrology as well as hydrodynamics of Lake Bosomtwe. After identifying parameters, establishing relationships between these parameters and continuously improving upon the developed model to appreciably mimic the water balance system observed from field data, the following conclusions are drawn:

1. Two seasons (rainy and dry) influence the hydrology of the lake. Of the two seasons, water loss mainly through evapotranspiration is minimal during the rainy season.

2. Rather than an absolute climatic stance as purported by earlier researchers, the hydrology of Lake Bosomtwe is also affected by anthropogenic factors such as water abstraction for domestic purposes and agricultural activities within the Lake's catchment. However, it is the climatic component that is the dominant factor responsible for the lake water level dynamics.
3. Of all the climatic components, rainfall is the major component responsible for determining the observed dynamic lake water level behaviour (noise). This behavioural trend in water level is very much attributed to seasonal variability in rainfall over the region.
4. Obtaining a co-efficient of determination (R^2) of 0.93 and an efficiency (Nash and Sutcliff) of 82.4%, the model is very good and thus suitable for making future predictions if fed with appropriate data.

6.2 Recommendations

From the findings of this research, the following actions are recommended:

1. Research institutions should invest in collecting data on the Lake parameters such as actual evapotranspiration and runoff from the field. This will facilitate research work and ensure that the data on parameters obtained are representative of what has ensued so that models specific to the catchment area can be developed or improved upon to enhance our knowledge and understanding of the resource.

2. Research institutions within the country should also focus their research around the development of climate models and synthetic weather generators for Ghana so that better future climate scenarios could be generated for research purposes as well as the

development of policies by decision makers and managers in order to better prepare for an uncertain future.

3. Managers of the Lake, together with the appropriate institutions of government such as Town and Country Planning, should invest into the earmarking of certain areas within the catchment for reforestation purposes. After which the Forestry Commission should vigorously embark on reforesting these demarcated areas in order to induce a microclimate that will readily mitigate the progressive increase in average temperature over the catchment area. By so doing, the depreciation in water levels will reduce.

4. Alternative sources of potable water for domestic use should be made readily available to the communities within the catchment area by the appropriate authorities so as to also reduce water demand on the resource.

5. The rate at which land use(s) or land cover changes occur should be carefully monitored and controlled by the managers of the Lake as well as all other appropriate authorities since that affects climatic conditions as well as runoff characteristics.

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APPENDICES

Appendix 1 Model equations for Lake Bosomtwe

1. Catchment__surface_area =

Sb__Closed_forest+Sb__Grassland+Sb__Open_forest+Sb__Settlement+Sb__Shrubs_and_trees+Sa__Closed_forest+Sa__Grassland+Sa__Open_Forest+Sa__Settlement+Sa__Shrubs_and_Trees

2. Sa__Closed_forest(t) = Sa__Closed_forest(t - dt)
INIT Sa__Closed_forest = 1743278269000

3. Sa__Grassland(t) = Sa__Grassland(t - dt)
INIT Sa__Grassland = 125554319000

4. Sa__Open_Forest(t) = Sa__Open_Forest(t - dt)
INIT Sa__Open_Forest = 174816535000

5. Sa__Settlement(t) = Sa__Settlement(t - dt)
INIT Sa__Settlement = 14580000000

6. Sa__Shrubs_and_Trees(t) = Sa__Shrubs_and_Trees(t - dt) INIT Sa__Shrubs_and_Trees = 293267377000

7. Sb__Closed_forest(t) = Sb__Closed_forest(t - dt)
INIT Sb__Closed_forest = 1261596895000

8. Sb__Grassland(t) = Sb__Grassland(t - dt)
INIT Sb__Grassland = 441954474000

9. Sb__Open_forest(t) = Sb__Open_forest(t - dt)
INIT Sb__Open_forest = 384192622000

10. Sb__Settlement(t) = Sb__Settlement(t - dt)
INIT Sb__Settlement = 42896420000

11. Sb__Shrubs_and_trees(t) = Sb__Shrubs_and_trees(t - dt) INIT Sb__Shrubs_and_trees = 995238798000

12. Volume_of__Lake_water(t) = Volume_of__Lake_water(t - dt) + (Volume_of__Direct_precipitation + Surface_Runoff_1 + Surface_Runoff_2 + Surface_Runoff_3 + Surface_Runoff_4 + Surface_Runoff_5 + Surface_Runoff_6 + Surface_Runoff_7 + Surface_Runoff_8 + Surface_Runoff_9 + Surface_Runoff_10 - Water__Withdrawal - Sim__Evaporation_from__lake_surface_2 - Sim__Evapotranspiration_from__land_surface) * dt

13. INIT Volume_of__Lake_water = (76820*Lake__Surface__Area)

INFLOWS:

14. Volume_of__Direct_precipitation = (Rainfall*Lake__Surface__Area)

15. Lake__Surface__Area = 48842880000000

16. Volume_of__Surface_Runoff = Surface_Runoff_5 + Surface_Runoff_4 + Surface_Runoff_3 + Surface_Runoff_2 + Surface_Runoff_1 + Surface_Runoff_6 + Surface_Runoff_7 + Surface_Runoff_8 + Surface_Runoff_9 + Surface_Runoff_10

17. Surface_Runoff_5 = ((Rainfall-Initial_abstraction_5) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_5)) *Sb__Shrubs_and_trees

18. Surface_Runoff_4 = ((Rainfall-Initial_abstraction_4) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_4)) *Sb__Settlement

19. Surface_Runoff_3 = ((Rainfall-Initial_abstraction_3) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_3)) *Sb__Open_forest

20. Surface_Runoff_2 = ((Rainfall-Initial_abstraction_2) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_2)) *Sb__Grassland

21. Surface_Runoff_1 = ((Rainfall-Initial_abstraction) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins)) *Sb__Closed_forest

22. Surface_Runoff_6 = ((Rainfall-Initial_abstraction_6) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_6)) *Sa__Closed_forest

23. Surface_Runoff_7 = ((Rainfall-Initial_abstraction_7) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_7)) *Sa__Grassland

24. Surface_Runoff_8 = ((Rainfall-Initial_abstraction_8) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_8)) *Sa__Open_Forest

25. Surface_Runoff_9 = ((Rainfall-Initial_abstraction_9) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_9)) *Sa__Settlement

26. Surface_Runoff_10 = ((Rainfall-Initial_abstraction_10) ^2) / ((Rainfall+0.8*max_water_absorbed_after_runoff_begins_10)) *Sa__Shrubs_and_Trees

27. Initial_abstraction_1 = 0.2*max_water_absorbed_after_runoff_begins_1

28. Initial_abstraction_10 = 0.2*max_water_absorbed_after_runoff_begins_10

29. Initial_abstraction_2 = 0.2*max_water_absorbed_after_runoff_begins_2
30. Initial_abstraction_3 = 0.2*max_water_absorbed_after_runoff_begins_3
31. Initial_abstraction_4 = 0.2*max_water_absorbed_after_runoff_begins_4
32. Initial_abstraction_5 = 0.2*max_water_absorbed_after_runoff_begins_5
33. Initial_abstraction_6 = 0.2*max_water_absorbed_after_runoff_begins_6
34. Initial_abstraction_7 = 0.2*max_water_absorbed_after_runoff_begins_7
35. Initial_abstraction_8 = 0.2*max_water_absorbed_after_runoff_begins_8
36. Initial_abstraction_9 = 0.2*max_water_absorbed_after_runoff_begins_9
37. max_water_absorbed_after_runoff_begins_1 = (1000/Runoff_curve_number_for_Soil_A_1)-10
38. max_water_absorbed_after_runoff_begins_10 = (1000/Runoff_curve_number_for_Soil_A_10)-10
39. max_water_absorbed_after_runoff_begins_2 = (1000/Runoff_curve_number_for_Soil_A_2)-10
40. max_water_absorbed_after_runoff_begins_3 = (1000/Runoff_curve_number_for_Soil_A_3)-10
41. max_water_absorbed_after_runoff_begins_4 = (1000/Runoff_curve_number_for_Soil_A_4)-10
42. max_water_absorbed_after_runoff_begins_5 = (1000/Runoff_curve_number_for_Soil_A_5)-10
43. max_water_absorbed_after_runoff_begins_6 = (1000/Runoff_curve_number_for_Soil_A_6)-10
44. max_water_absorbed_after_runoff_begins_7 = (1000/Runoff_curve_number_for_Soil_A_7)-10
45. max_water_absorbed_after_runoff_begins_8 = (1000/Runoff_curve_number_for_Soil_A_8)-10

46. max_water_absorbed_after_runoff_begins_9 = (1000/Runoff_curve_number_for_Soil_A_9)-10

47. Runoff_curve_number_for_Soil_A_1 = 58

48. Runoff_curve_number_for_Soil_A_10 = 39

49. Runoff_curve_number_for_Soil_A_2 = 69

50. Runoff_curve_number_for_Soil_A_3 = 65

51. Runoff_curve_number_for_Soil_A_4 = 85

52. Runoff_curve_number_for_Soil_A_5 = 61

53. Runoff_curve_number_for_Soil_A_6 = 32

54. Runoff_curve_number_for_Soil_A_7 = 49

55. Runoff_curve_number_for_Soil_A_8 = 44

56. Runoff_curve_number_for_Soil_A_9 = 77

OUTFLOWS:

57. Water__Withdrawal = Population*Annual_withdrawal__per_capita

58. Population(t) = Population(t - dt) + (Population_growth) * dt INIT Population = 6000

59. Population_growth = Population*Growth_rate

60. Growth_rate = 0.03/12

61. Annual_withdrawal__per_capita = 48000000000/12

62. Sim__Evaporation_from__lake_surface_2 = ((0.0477*Solar_Radiation_Rs*(SQRT(Air__Temperature_Ta+9.5)) - 2.43* (Solar_Radiation_Rs/Extraterrestrial__Radiation_Ra)+0.09*(Air__Temperature_Ta+20) *(1- (Relative_Humidity_2/100))) *Days_in_each_month_2 *Lake__Surface__Area) *K_factor

63. Sim__Evapotranspiration_from__land_surface = (((0.408*(Slope_vapour_pressure)*(Net_radiation_Rn-Soil_heat__flux_density_G) + (Psychrometric_constant*((900/(Air__Temperature_Ta+273))*(Wind_speed)*(Mean_Sa t uration__Vapour_pressure_Es-Actual_vapour_pressure))) / (Slope_vapour_pressure+(Psychrometric_constant*(1+(0.34*Wind_speed)))))) *Days_in_each_month_2*Catchment__surface_area)*L_factor

64. K_factor = 0.87

65. L_factor = 0.87

66. Psychrometric_constant = 0.065

67. Sim__Lake_water_level__gauge = (Volume_of__Lake_water/Lake__Surface__Area) Actual_vapour_pressure = GRAPH(TIME)

(1.00, 2.34), (2.00, 2.49), (3.00, 2.66), (4.00, 2.80), (5.00, 2.72), (6.00, 2.62), (7.00, 2.56), (8.00, 2.62), (9.00, 2.50), (10.0, 2.72), (11.0, 2.59), (12.0, 2.15), (13.0, 2.34), (14.0, 2.35), (15.0, 2.67), (16.0, 2.69), (17.0, 2.78), (18.0, 2.60), (19.0, 2.53), (20.0, 2.62), (21.0, 2.60), (22.0, 2.61), (23.0, 2.69), (24.0, 1.95), (25.0, 1.91), (26.0, 2.60), (27.0, 2.64), (28.0, 2.76), (29.0, 2.83), (30.0, 2.56), (31.0, 2.53), (32.0, 2.43), (33.0, 2.56), (34.0, 2.53), (35.0, 2.56), (36.0, 2.02), (37.0, 2.28), (38.0, 2.69), (39.0, 2.55), (40.0, 2.73), (41.0, 2.83), (42.0, 2.66), (43.0, 2.50), (44.0, 2.58), (45.0, 2.66), (46.0, 2.63), (47.0, 2.59), (48.0, 2.26), (49.0, 2.00), (50.0, 2.60), (51.0, 2.83), (52.0, 2.86), (53.0, 2.84), (54.0, 2.71), (55.0, 2.62), (56.0, 2.56), (57.0, 2.68), (58.0, 2.76), (59.0, 2.73), (60.0, 2.37), (61.0, 2.08), (62.0, 2.21), (63.0, 2.68), (64.0, 2.81), (65.0, 2.84), (66.0, 2.77), (67.0, 2.66), (68.0, 2.64), (69.0, 2.69), (70.0, 2.84), (71.0, 2.88), (72.0, 2.61), (73.0, 2.48), (74.0, 2.24), (75.0, 2.88), (76.0, 2.89), (77.0, 2.84), (78.0, 2.80), (79.0, 2.61), (80.0, 2.59), (81.0, 2.71), (82.0, 2.84), (83.0, 2.83), (84.0, 2.58), (85.0, 2.50), (86.0, 2.84), (87.0, 2.85), (88.0, 2.90), (89.0, 2.97), (90.0, 2.90), (91.0, 2.71), (92.0, 2.64), (93.0, 2.73), (94.0, 2.68), (95.0, 2.76), (96.0, 2.51), (97.0, 1.90), (98.0, 2.67), (99.0, 2.77), (100, 2.89), (101, 2.93), (102, 2.70), (103, 2.57), (104, 2.47), (105, 2.61), (106, 2.65), (107, 2.51), (108, 2.60), (109, 1.95), (110, 2.70), (111, 2.57), (112, 2.74), (113, 2.73), (114, 2.74), (115, 2.58), (116, 2.60), (117, 2.69), (118, 2.73), (119, 2.76), (120, 2.46), (121, 2.29), (122, 2.53), (123, 2.76), (124, 2.86), (125, 2.91), (126, 2.72), (127, 2.61), (128, 2.52), (129, 2.56), (130, 2.78), (131, 2.64), (132, 2.21), (133, 1.89), (134, 2.60), (135, 2.78), (136, 2.92), (137, 2.90), (138, 2.76), (139, 2.86), (140, 2.65), (141, 2.72), (142, 2.69), (143, 2.71), (144, 2.54), (145, 2.73), (146, 2.79), (147, 2.88), (148, 2.91), (149, 2.81), (150, 2.78), (151, 2.64), (152, 2.69), (153, 2.64), (154, 2.69), (155, 2.64), (156, 2.76), (157, 2.68), (158, 2.39), (159, 2.70), (160, 2.80), (161, 2.95), (162, 2.78), (163, 2.58), (164, 2.61), (165, 2.73), (166, 2.84), (167, 2.77), (168, 2.60), (169, 2.23), (170, 2.71), (171, 2.91), (172, 3.05), (173, 2.88), (174, 2.83), (175, 2.69), (176, 2.58), (177, 2.74), (178, 2.76), (179, 2.76), (180, 2.73), (181, 2.62), (182, 2.43), (183, 2.83), (184, 2.84), (185, 2.81), (186, 2.78), (187, 2.73), (188, 2.56), (189, 2.66), (190, 2.68), (191, 2.73), (192, 2.53), (193, 2.68), (194, 2.18), (195, 2.81), (196, 2.94), (197, 2.87), (198, 2.82), (199, 2.64), (200, 2.65), (201, 2.75), (202, 2.81), (203, 2.83), (204, 2.53), (205, 2.46), (206, 2.49), (207, 2.92), (208, 2.90), (209, 2.96), (210, 2.89), (211, 2.78), (212, 2.65), (213, 2.68), (214, 2.84), (215, 2.91), (216, 3.00), (217, 2.47), (218, 2.73), (219, 2.97), (220, 2.97), (221, 2.90), (222, 2.77), (223, 2.73), (224, 2.56), (225, 2.69), (226, 2.86), (227, 2.86), (228, 2.73), (229, 2.53), (230, 2.84), (231, 2.85), (232, 2.90), (233, 2.94), (234, 2.78), (235, 2.56), (236, 2.53), (237, 2.78), (238, 2.91), (239, 2.87), (240, 2.61), (241, 2.60), (242, 2.57), (243, 2.67), (244, 2.93), (245, 2.80), (246, 2.67), (247, 2.58), (248, 2.60), (249, 2.76), (250, 2.80), (251, 2.85), (252, 2.89), (253, 1.99), (254, 2.85), (255, 2.84), (256, 2.95), (257, 2.83), (258, 2.73), (259, 2.51), (260, 2.47), (261, 2.74), (262, 2.85), (263, 2.87), (264, 2.75), (265, 2.73), (266, 2.85), (267, 2.76), (268, 2.98), (269, 2.86), (270, 2.87), (271, 2.69), (272, 2.60), (273, 2.75), (274, 2.85), (275, 2.68), (276, 2.49), (277, 1.90), (278, 2.72), (279, 2.77), (280, 2.84), (281, 2.90), (282, 2.84), (283, 2.77), (284, 2.70), (285, 2.88), (286, 2.84), (287, 2.87), (288, 2.67), (289, 1.66), (290, 2.49), (291, 2.80), (292, 2.90), (293, 2.95), (294, 2.85), (295, 2.77), (296, 2.69), (297, 2.82), (298, 2.88), (299, 2.90), (300, 2.78), (301, 2.23), (302, 2.91), (303, 2.93), (304, 2.95), (305, 2.76), (306, 2.92), (307, 2.76), (308, 2.77), (309, 2.84), (310, 2.93), (311, 2.83), (312, 2.93), (313, 2.89), (314, 2.93), (315, 2.98), (316, 3.02), (317, 3.03), (318, 2.95), (319, 2.75), (320, 2.80), (321, 2.90), (322, 3.00), (323, 2.96), (324, 2.87), (325, 2.29), (326, 2.67), (327, 2.90), (328, 2.94), (329, 2.99), (330, 2.93), (331, 2.73), (332, 2.70), (333, 2.85), (334, 2.89), (335, 2.92), (336, 2.84), (337, 2.56), (338, 2.93), (339, 3.22), (340, 3.07), (341, 3.10), (342, 2.90), (343, 2.82), (344, 2.71), (345, 3.01), (346, 2.89), (347, 2.93), (348, 2.99), (349, 2.14), (350, 2.65), (351, 2.93), (352, 2.98), (353, 2.90), (354, 2.86), (355, 2.69), (356, 2.61), (357, 2.85), (358, 2.89), (359, 2.84), (360, 2.62)

Air__Temperature_Ta = GRAPH(TIME)

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Days_in_each_month_2 = GRAPH(TIME)

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Extraterrestrial__Radiation_Ra = GRAPH(TIME)

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Mean_Saturation__Vapour_pressure_Es = GRAPH(TIME)

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Net_radiation_Rn = GRAPH(TIME)

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Obs__Lake_Water_Level = GRAPH(TIME)

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Rainfall = GRAPH(TIME)

(1.00, 0.00), (2.00, 8.90), (3.00, 134), (4.00, 80.5), (5.00, 133), (6.00, 180), (7.00, 277), (8.00, 171), (9.00, 215), (10.0, 139), (11.0, 44.4), (12.0, 1.30), (13.0, 18.5), (14.0, 14.5), (15.0, 247), (16.0, 167), (17.0, 105), (18.0, 159), (19.0, 417), (20.0, 96.5), (21.0, 203), (22.0, 99.7), (23.0, 110), (24.0, 0.00), (25.0, 0.00), (26.0, 132), (27.0, 64.4), (28.0, 70.7), (29.0, 155), (30.0, 268), (31.0, 176), (32.0, 29.4), (33.0, 114), (34.0, 171), (35.0, 13.0), (36.0, 0.00), (37.0, 5.90), (38.0, 64.8), (39.0, 110), (40.0, 171), (41.0, 46.3), (42.0, 246), (43.0, 157), (44.0, 192), (45.0, 189), (46.0, 74.4), (47.0, 3.00), (48.0, 13.5), (49.0, 0.00), (50.0, 10.0), (51.0, 310), (52.0, 136), (53.0, 111), (54.0, 342), (55.0, 139), (56.0, 15.0), (57.0, 186), (58.0, 136), (59.0, 38.6), (60.0, 78.9), (61.0, 53.7), (62.0, 2.30), (63.0, 113), (64.0, 77.2), (65.0, 126), (66.0, 310), (67.0, 89.3), (68.0, 177), (69.0, 281), (70.0, 186), (71.0, 39.5), (72.0, 8.20), (73.0, 35.8), (74.0, 69.1), (75.0, 110), (76.0, 199), (77.0, 115), (78.0, 126), (79.0, 22.6), (80.0, 29.6), (81.0, 159), (82.0, 138), (83.0, 105), (84.0, 83.4), (85.0, 54.8), (86.0, 83.9), (87.0, 77.8), (88.0, 133), (89.0, 307), (90.0, 172), (91.0, 88.1), (92.0, 69.7), (93.0, 143), (94.0, 123), (95.0, 23.7), (96.0, 0.1), (97.0, 3.60), (98.0, 5.50), (99.0, 74.3), (100, 153), (101, 150), (102, 133), (103, 79.2), (104, 30.4), (105, 313), (106, 49.2), (107, 65.6), (108, 7.10), (109, 2.00), (110, 53.1), (111, 118), (112, 153), (113, 140), (114, 339), (115, 31.0), (116, 103), (117, 168), (118, 257), (119, 52.4), (120, 26.7), (121, 0.00), (122, 7.30), (123, 52.1), (124, 195), (125, 209), (126, 116), (127, 96.5), (128, 63.1), (129, 156), (130, 179), (131, 35.2), (132, 0.00), (133, 0.00), (134, 0.7), (135, 122), (136, 199), (137, 176), (138, 155), (139, 137), (140, 149), (141, 139), (142, 95.7), (143, 40.0), (144, 116), (145, 3.70), (146, 80.2), (147, 72.2), (148, 112), (149, 146), (150, 106), (151, 203), (152, 110), (153, 72.5), (154, 81.8), (155, 2.80), (156, 51.9), (157, 53.7), (158, 33.0), (159, 138), (160, 297), (161, 219), (162, 250), (163, 73.4), (164, 59.0), (165, 96.3), (166, 162), (167, 11.1), (168, 11.3), (169, 51.8), (170, 26.6), (171, 35.9), (172, 267), (173, 183), (174, 119), (175, 56.5), (176, 75.6), (177, 74.7), (178, 76.5), (179, 23.5), (180, 31.7), (181, 61.3), (182, 25.9), (183, 110), (184, 217), (185, 102), (186, 218), (187, 203), (188, 114), (189, 135), (190, 204), (191, 39.0), (192, 0.00), (193, 62.4), (194, 7.20), (195, 111), (196, 206), (197, 169), (198, 373), (199, 153), (200, 65.3), (201, 144), (202, 120), (203, 77.8), (204, 0.00), (205, 0.00), (206, 21.5), (207, 220), (208, 163), (209, 107), (210, 150), (211, 113), (212, 48.6), (213, 217), (214, 113), (215, 15.5), (216, 18.4), (217, 1.60), (218, 7.60), (219, 99.7), (220, 239), (221, 205), (222, 266), (223, 281), (224, 75.8), (225, 124), (226, 319), (227, 45.2), (228, 5.40), (229, 32.9), (230, 74.5), (231, 73.1), (232, 130), (233, 189), (234, 255), (235, 95.3), (236, 26.8), (237, 99.5), (238, 180), (239, 163), (240, 30.9), (241, 25.8), (242, 70.8), (243, 164), (244, 101), (245, 72.3), (246, 41.1), (247, 229), (248, 115), (249, 235), (250, 232), (251, 43.5), (252, 76.5), (253, 12.5), (254, 48.9), (255, 84.2), (256, 146), (257, 272), (258, 121), (259, 18.3), (260, 36.7), (261, 174), (262, 237), (263, 49.8), (264, 29.8), (265, 111), (266, 92.3), (267, 113), (268, 66.9), (269, 187), (270, 145), (271, 66.7), (272, 65.2), (273, 111), (274, 158), (275, 13.4), (276, 3.70), (277, 0.2), (278, 16.9), (279, 56.2), (280, 311), (281, 164), (282, 176), (283, 193), (284, 118), (285, 535), (286, 154), (287, 51.7), (288, 19.8), (289, 0.00), (290, 53.7), (291, 97.4), (292, 132), (293, 240), (294, 287), (295, 131), (296, 193), (297, 171), (298, 75.1), (299, 18.3), (300, 54.8), (301, 0.00), (302, 131), (303, 111), (304, 140), (305, 165), (306, 377), (307, 274), (308, 17.6), (309, 99.3), (310, 139), (311, 45.2), (312, 33.4), (313, 14.7), (314, 52.7), (315, 52.6), (316, 77.3), (317, 109), (318, 226), (319, 83.3), (320, 113), (321, 166), (322, 184), (323, 80.9), (324, 38.3), (325, 65.8), (326, 136), (327, 231), (328, 123), (329, 100), (330, 244), (331, 179), (332, 60.6), (333, 156), (334, 188), (335, 38.9), (336, 0.00), (337, 48.1), (338, 74.9), (339, 92.0), (340, 119), (341, 271), (342, 380), (343, 93.8), (344, 3.40), (345, 82.5), (346, 226), (347, 70.6), (348, 60.6), (349, 0.00), (350, 54.7), (351, 108), (352, 168), (353, 207), (354, 115), (355, 138), (356, 6.20), (357, 220), (358, 210), (359, 80.6), (360, 42.0)

Relative_Humidity_2 = GRAPH(TIME)

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Slope_vapour_pressure = GRAPH(TIME)

(1.00, 0.213), (2.00, 0.0248), (3.00, 0.221), (4.00, 0.221), (5.00, 0.209), (6.00, 0.165), (7.00, 0.189), (8.00, 0.193), (9.00, 0.189), (10.0, 0.203), (11.0, 0.203), (12.0, 0.193), (13.0, 0.209), (14.0, 0.221), (15.0, 0.215), (16.0, 0.209), (17.0, 0.207), (18.0, 0.195), (19.0, 0.185), (20.0, 0.189), (21.0, 0.191), (22.0, 0.198), (23.0, 0.203), (24.0, 0.189), (25.0, 0.202), (26.0, 0.223), (27.0, 0.209), (28.0, 0.216), (29.0, 0.216), (30.0, 0.193), (31.0, 0.183), (32.0, 0.182), (33.0, 0.191), (34.0, 0.193), (35.0, 0.205), (36.0, 0.195), (37.0, 0.202), (38.0, 0.223), (39.0, 0.209), (40.0, 0.216), (41.0, 0.216), (42.0, 0.193), (43.0, 0.183), (44.0, 0.182), (45.0, 0.191), (46.0, 0.193), (47.0, 0.205), (48.0, 0.195), (49.0, 0.203), (50.0, 0.235), (51.0, 0.221), (52.0, 0.216), (53.0, 0.211), (54.0, 0.196), (55.0, 0.187), (56.0, 0.183), (57.0, 0.192), (58.0, 0.203), (59.0, 0.21), (60.0, 0.192), (61.0, 0.202), (62.0, 0.223), (63.0, 0.222), (64.0, 0.217), (65.0, 0.212), (66.0, 0.198), (67.0, 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(281, 0.21), (282, 0.204), (283, 0.196), (284, 0.192), (285, 0.196), (286, 0.202), (287, 0.208), (288, 0.21), (289, 0.2), (290, 0.224), (291, 0.224), (292, 0.216), (293, 0.213), (294, 0.203), (295, 0.196), (296, 0.193), (297, 0.199), (298, 0.209), (299, 0.221), (300, 0.216), (301, 0.215), (302, 0.224), (303, 0.223), (304, 0.217), (305, 0.205), (306, 0.203), (307, 0.191), (308, 0.188), (309, 0.196), (310, 0.203), (311, 0.21), (312, 0.218), (313, 0.222), (314, 0.234), (315, 0.229), (316, 0.226), (317, 0.218), (318, 0.204), (319, 0.195), (320, 0.196), (321, 0.199), (322, 0.21), (323, 0.211), (324, 0.217), (325, 0.207), (326, 0.217), (327, 0.216), (328, 0.221), (329, 0.218), (330, 0.202), (331, 0.191), (332, 0.19), (333, 0.197), (334, 0.205), (335, 0.218), (336, 0.215), (337, 0.211), (338, 0.218), (339, 0.222), (340, 0.216), (341, 0.214), (342, 0.195), (343, 0.189), (344, 0.186), (345, 0.2), (346, 0.203), (347, 0.214), (348, 0.211), (349, 0.217), (350, 0.236), (351, 0.223), (352, 0.224), (353, 0.21), (354, 0.201), (355, 0.189), (356, 0.184), (357, 0.197), (358, 0.203), (359, 0.211), (360, 0.203)

Soil_heat__flux_density_G = GRAPH(TIME)

(1.00, 0.346), (2.00, 0.077), (3.00, 0.003), (4.00, -0.035), (5.00, -0.098), (6.00, -0.122), (7.00, 0.017), (8.00, 0.031), (9.00, 0.098), (10.0, 0.08), (11.0, -0.038), (12.0, 0.035), (13.0, 0.21), (14.0, 0.08), (15.0, -0.087), (16.0, -0.01), (17.0, -0.14), (18.0, -0.213), (19.0, -0.031), (20.0, 0.056), (21.0, 0.112), (22.0, 0.084), (23.0, -0.028), (24.0, -0.017), (25.0, 0.185), (26.0, 0.042), (27.0, -0.042), (28.0, 0.049), (29.0, -0.514), (30.0, -0.224), (31.0, -0.077), (32.0, 0.056), (33.0, 0.077), (34.0, 0.094), (35.0, 0.01), (36.0, -0.017), (37.0, 0.185), (38.0, 0.035), (39.0, -0.115), (40.0, -0.028), (41.0, -0.154), (42.0, -0.189), (43.0, -0.098), (44.0, 0.031), (45.0, 0.073), (46.0, 0.087), (47.0, 0.059), (48.0, -0.042), (49.0, 0.276), (50.0, 0.122), (51.0, -0.042), (52.0, -0.07), (53.0, -0.14), (54.0, -0.175), (55.0, -0.105), (56.0, -0.007), (57.0, 0.108), (58.0, 0.14), (59.0, -0.052), (60.0, -0.101), (61.0, 0.091), (62.0, 0.087), (63.0, 0.077), (64.0, -0.157), (65.0, -0.133), (66.0, -0.119), (67.0, 0.112), (68.0, 0.021), (69.0, 0.091), (70.0, 0.154), (71.0, 0.045), (72.0, -0.01), (73.0, 0.049), (74.0, 0.192), (75.0, -0.0385), (76.0, -0.059), (77.0, -0.07), (78.0, -0.175), (79.0, -0.147), (80.0, 0.00), (81.0, 0.108), (82.0, 0.08), (83.0, 0.028), (84.0, -0.003), (85.0, 0.101), (86.0, 0.101), (87.0, -0.14),

(88.0, -0.101), (89.0, -0.063), (90.0, -0.147), (91.0, -0.0665), (92.0, 0.126), (93.0, 0.105), (94.0, 0.133), (95.0, 0.035), (96.0, 0.0525), (97.0, 0.21), (98.0, 0.157), (99.0, -0.077), (100, 0.0385), (101, -0.101), (102, -0.182), (103, -0.147), (104, 0.014), (105, 0.133), (106, 0.049), (107, 0.00), (108, 0.028), (109, 0.192), (110, 0.021), (111, -0.105), (112, -0.135), (113, -0.105), (114, -0.182), (115, -0.105), (116, 0.0315), (117, 0.109), (118, 0.171), (119, 0.014), (120, -0.007), (121, 0.154), (122, 0.133), (123, -0.14), (124, -0.059), (125, -0.126), (126, -0.175), (127, -0.091), (128, -0.143), (129, 0.094), (130, 0.091), (131, 0.028), (132, -0.028), (133, 0.234), (134, 0.108), (135, -0.003), (136, 0.021), (137, -0.105), (138, -0.035), (139, -0.094), (140, 0.017), (141, 0.073), (142, 0.143), (143, 0.035), (144, -0.073), (145, 0.084), (146, 0.056), (147, -0.052), (148, -0.108), (149, -0.066), (150, -0.168), (151, -0.052), (152, 0.024), (153, 0.087), (154, 0.129), (155, -0.017), (156, -0.024), (157, 0.084), (158, 0.08), (159, -0.129), (160, -0.168), (161, -0.234), (162, -0.168), (163, -0.133), (164, 0.028), (165, 0.164), (166, 0.108), (167, 0.059), (168, -0.035), (169, 0.101), (170, 0.164), (171, 0.094), (172, -0.063), (173, -0.059), (174, -0.119), (175, -0.129), (176, 0.021), (177, 0.098), (178, 0.196), (179, 0.122), (180, 0.063), (181, 0.035), (182, 0.049), (183, -0.052), (184, -0.14), (185, 0.105), (186, -0.115), (187, -0.038), (188, 0.038), (189, 0.066), (190, 0.133), (191, 0.105), (192, 0.035), (193, 0.126), (194, 0.108), (195, -0.059), (196, -0.077), (197, -0.115), (198, -0.203), (199, -0.126), (200, -0.024), (201, 0.094), (202, 0.147), (203, -0.021), (204, 0.003), (205, 0.049), (206, 0.038), (207, -0.157), (208, -0.087), (209, -0.115), (210, -0.136), (211, -0.105), (212, -0.038), (213, 0.164), (214, 0.147), (215, 0.112), (216, 0.042), (217, 0.115), (218, 0.084), (219, -0.035), (220, 0.133), (221, -0.122), (222, -0.182), (223, -0.112), (224, 0.028), (225, 0.14), (226, 0.077), (227, 0.063), (228, 0.024), (229, 0.14), (230, 0.147), (231, -0.045), (232, -0.014), (233, -0.129), (234, 0.129), (235, -0.101), (236, 0.084), (237, 0.175), (238, 0.101), (239, 0.017), (240, 0.007), (241, 0.091), (242, 0.161), (243, -0.066), (244, -0.073), (245, -0.157), (246, -0.161), (247, -0.07), (248, 0.094), (249, 0.171), (250, 0.073), (251, 0.028), (252, -0.108), (253, 0.112), (254, 0.045), (255, 0.024), (256, -0.028), (257, -0.199), (258, -0.192), (259, -0.199), (260, 0.024), (261, 0.105), (262, 0.136), (263, 0.042), (264, 0.01), (265, 0.073), (266, 0.045), (267, -0.007), (268, -0.115), (269, 0.028), (270, -0.101), (271, -0.098), (272, -0.021), (273, 0.077), (274, 0.098), (275, 0.028), (276, -0.007), (277, 0.091), (278, 0.178), (279, -0.087), (280, -0.087), (281, -0.08), (282, -0.115), (283, -0.077), (284, 0.003), (285, 0.063), (286, 0.063), (287, 0.01), (288, -0.133), (289, 0.052), (290, 0.052), (291, -0.049), (292, -0.063), (293, -0.094), (294, -0.066), (295, -0.066), (296, 0.052), (297, 0.143), (298, 0.161), (299, 0.08), (300, 0.035), (301, 0.035), (302, 0.003), (303, -0.105), (304, 0.147), (305, -0.15), (306, -0.178), (307, -0.116), (308, 0.01), (309, 0.052), (310, 0.07), (311, 0.056), (312, 0.07), (313, 0.108), (314, 0.136), (315, 0.059), (316, 0.01), (317, -0.108), (318, 0.154), (319, -0.045), (320, 0.056), (321, 0.136), (322, 0.098), (323, 0.077), (324, -0.07), (325, 0.014), (326, 0.031), (327, 0.017), (328, -0.028), (329, -0.0875), (330, -0.15), (331, -0.038), (332, 0.056), (333, 0.129), (334, 0.119), (335, 0.077), (336, -0.017), (337, 0.045), (338, 0.035), (339, 0.126), (340, -0.059), (341, -0.185), (342, -0.147), (343, -0.105), (344, 0.073), (345, 0.129), (346, 0.115), (347, 0.056), (348, 0.038), (349, 0.21), (350, 1.98), (351, 1.98), (352, 1.90), (353, 1.84), (354, 1.76), (355, 1.72), (356, 1.81), (357, 1.85), (358, 1.90), (359, 1.85), (360, 0.00)
Solar_Radiation_Rs = GRAPH(TIME)

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Wind_speed = GRAPH(TIME)

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Appendix 2 Rainfall Statistics of Kumasi from the period of 1984 to 2013

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Rainfall	360	0	360	0.0000	534.5000	112.7464	87.5119

Appendix 3 Standard normal homogeneity test – (Rainfall)

T0	3.0799
T	2
p-value (Two-tailed)	0.8083
Alpha	0.05

The p-value has been computed using 10000 Monte Carlo simulations. Time elapsed: 0s. 99% confidence interval on the p-value: (0.7982, 0.8184)

Test interpretation:

H0: Data are homogeneous

Ha: There is a date at which there is a change in the data

As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0. The risk to reject the null hypothesis H0 while it is true is 80.83%.

Appendix

4 Temperature statistics of Kumasi from the January 1984 to December 2013

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Air Temperature Ta	360	0	360	23.9	30.4	26.7357	1.2711

Appendix 5 Standard normal homogeneity Test (Temperature)

T0	7.9043
T	4
p-value (Two-tailed)	0.138
Alpha	0.05

The p-value has been computed using 10000 Monte Carlo simulations. Time elapsed: 1s. 99% confidence interval on the p-value: (0.1291, 0.1469)

Test interpretation:

H0: Data are homogeneous

Ha: There is a date at which there is a change in the data

As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

The risk to reject the null hypothesis H0 while it is true is 13.80%.

6 Relative Humidity statistics of Kumasi from January 1984 to December 2013

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Relative Humidity	360	0	360	42	90	77.8806	8.2658

Appendix 7 Standard Homogeneity Test (Relative Humidity)

T0	14.1766
T	135
p-value (Two-tailed)	0.0237
Alpha	0.05

The p-value has been computed using 10000 Monte Carlo simulations. Time elapsed: 0s. 99% confidence interval on the p-value: (0.0198, 0.0276)

Test interpretation:

H0: Data are homogeneous

Ha: There is a date at which there is a change in the data

As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

The risk to reject the null hypothesis H0 while it is true is lower than 2.37%.

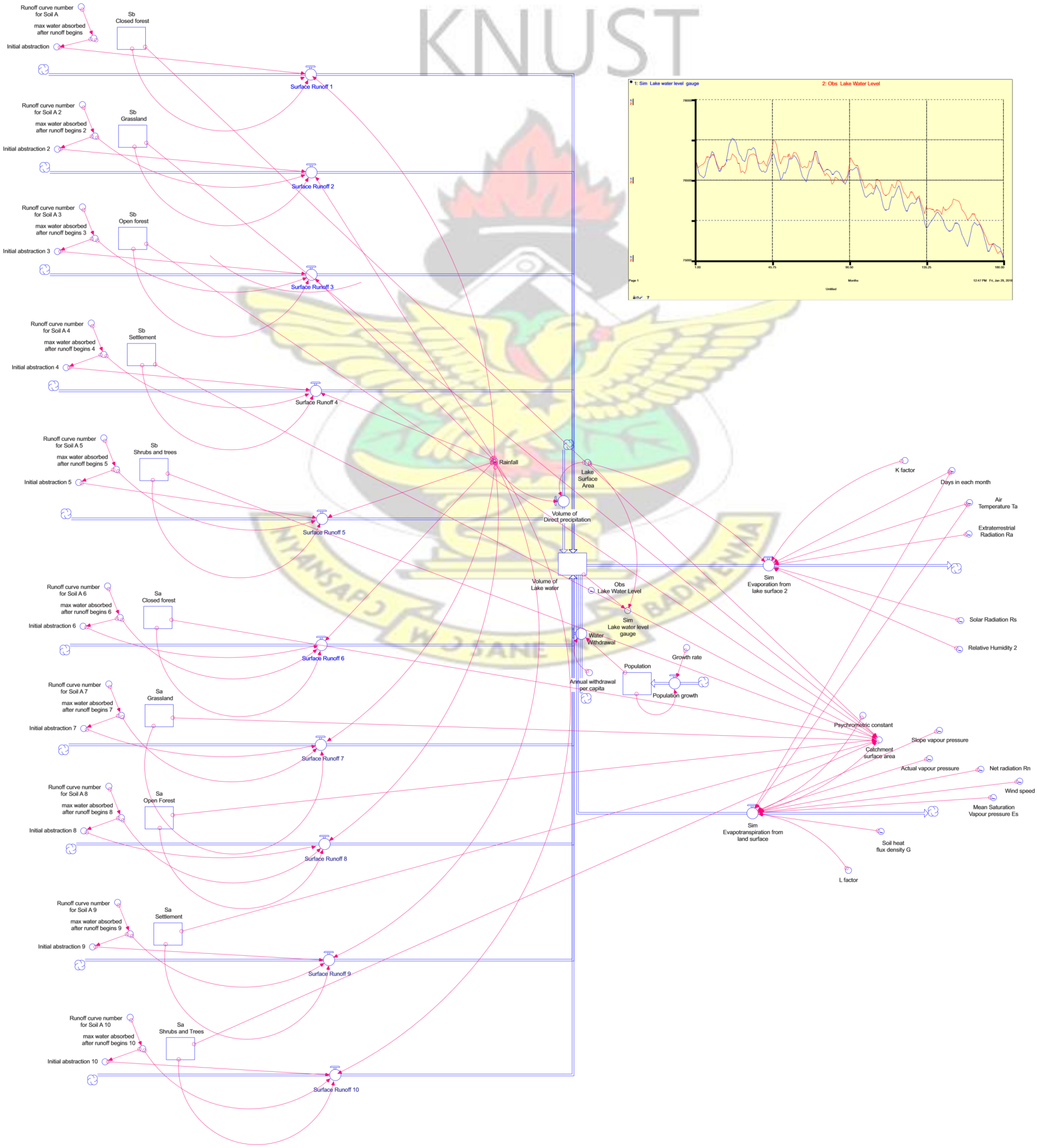
Runoff curve number for Soil A
max water absorbed after runoff begins
Initial abstraction
Sb Closed forest
Surface Runoff 1
Runoff curve number for Soil A 2
max water absorbed after runoff begins 2
Initial abstraction 2
Sb Grassland
Surface Runoff 2
Runoff curve number for Soil A 3
max water absorbed after runoff begins 3
Initial abstraction 3
Sb Open forest
Surface Runoff 3
Runoff curve number for Soil A 4
max water absorbed after runoff begins 4
Initial abstraction 4
Sb Settlement
Surface Runoff 4
Runoff curve number for Soil A 5
max water absorbed after runoff begins 5
Initial abstraction 5
Sb Shrubs and trees
Surface Runoff 5
Runoff curve number for Soil A 6
max water absorbed after runoff begins 6
Initial abstraction 6
Sa Closed forest
Surface Runoff 6
Runoff curve number for Soil A 7
max water absorbed after runoff begins 7
Initial abstraction 7
Sa Grassland
Surface Runoff 7
Runoff curve number for Soil A 8
max water absorbed after runoff begins 8
Initial abstraction 8
Sa Open Forest
Surface Runoff 8
Runoff curve number for Soil A 9
max water absorbed after runoff begins 9
Initial abstraction 9
Sa Settlement
Surface Runoff 9
Runoff curve number for Soil A 10
max water absorbed after runoff begins 10
Initial abstraction 10
Sa Shrubs and Trees
Surface Runoff 10
Rainfall
Lake Surface Area
Volume of Direct precipitation
Volume of Lake water
Obs Lake Water Level
Sim Lake water level gauge
Water Withdrawal
Annual withdrawal per capita
Population
Growth rate
Population growth
K factor
Days in each month
Air Temperature Ta
Extraterrestrial Radiation Ra
Sim Evaporation from lake surface 2
Solar Radiation Rs
Relative Humidity 2
Psychrometric constant
Catchment surface area
Slope vapour pressure
Actual vapour pressure
Net radiation Rn
Wind speed
Mean Saturation Vapour pressure Es
Sim Evapotranspiration from land surface
Soil heat flux density G
L factor
1: Sim Lake water level gauge
2: Obs Lake Water Level
Months
Untitled

Figure 3.4 STELLA model developed for the water balance of Lake Bosomtwe