Modelling Climatic and Hydrological Variability in Lake Babati, Northern Tanzania

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Preface

This Master’s thesis is Marc Girons Lopez’s degree project in Physical Geography and Quaternary Geology, at the Department of Physical Geography and Quaternary Geology, Stockholm University. The Master’s thesis comprises 30 HECs (one term of full-time studies).

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Abstract

A good understanding of the local and regional water cycle and how it is modified by landscape changes may help policymakers take the pertinent decisions in order to avoid adverse effects of future hydro–climatic changes. This knowledge is of particular interest in the most vulnerable areas of the world such as the African continent. In this context the aim of this project is to model hydrological responses to possible changes in climatic conditions in Lake Babati, northern Tanzania. For this reason a water balance model specially designed to simulate lake level changes was adapted to Lake Babati and calibrated with the available local meteorological and hydrological data record covering the last decades. The necessary ambient condition changes to produce a dry–out and an overflow of the lake were investigated and the response of the system to future IPCC climate change projections was studied. The results show that for instance a temperature change of less than 3ºC or a precipitation change of around 100 mm/year could eventually bring the lake from a dry–out situation to an overflow situation. Furthermore, the IPCC derived scenarios show a clear tendency of the lake to increase its volume and reach the overflow level in a relatively short time.
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1. Introduction

In recent years climate change and its derived catastrophic events has been a global concern. Huge forest fires in Australia, extensive floods in central Europe or massive landslides in South America are but some of the most outstanding examples of the magnitude of these events (Cary 2002; Christensen & Christensen 2003; Porfiriev 2009; Schuster et al. 2002).

The most part of these phenomena have a close relationship with the water cycle (Bates et al. 2008). An excess of water is ultimately responsible for floods and landslides while a lack of it will inevitably lead to drought (Slaymaker et al. 2009). But water is not the only factor playing a key role. The considerable population increase in most parts of the world is leading to an unprecedented change in the landscape such as clearing of forests or drying of marshlands in order to create crop fields (IPCC 2010). These changes in the landscape may also contribute to triggering catastrophic events that otherwise would have not occurred (Diamond 2006; Smith & Petley 2008).

Therefore, it has become a crucial matter to understand the water cycle not only in the global scale but also in the regional and local scale, especially in the most vulnerable parts of the world (Gleick 1987; Jones 1997). A good understanding of the local and regional water cycle and how it is modified by landscape changes may help policymakers take the pertinent decisions in order to avoid adverse effects of future hydro–climatic changes that might otherwise undermine the area’s economy as well as endanger human lives (Gupta et al. 2007).

In this context the African continent is one of the most vulnerable areas in the world (Boko et al. 2007). In this area climate change effects are likely to be aggravated by the low adaptive capacity of the region. Food security and water availability are very likely to be compromised in most areas, ecosystem changes and inundations of low–lands may affect entire regions and the possible spread of diseases like malaria is a serious concern in southern Africa and the East African Highlands.

Several approaches have been applied to try to understand and predict climate and hydrological variability (Jansen et al. 2007). For some decades lake studies have proven useful to determine past climate changes and extreme events in different parts of the world and in Easter Africa in particular (Ryner et al. 2008; Verschuren et al. 2000).
However, each system has its own specific characteristics and may respond differently to the current climate change scenario. Therefore, the survival of people and their way of life in a vulnerable environment like the African continent may depend on the knowledge of the mechanisms driving the environmental changes in local scales.

1.1 Aim of the project

For this project the hydro–climatic conditions of Lake Babati and its catchment (Northern Tanzania) are studied as this area represents a site where extensive landscape changes during the last century combined with irregular precipitation patterns have triggered several flooding events over a populated area (Strömquist & Johansson 1990). The main purpose of the present study is to accurately reconstruct and represent the recent Lake Babati level changes using hydro–climatic modelling. The relative importance of the different hydro–meteorological parameters is also tested, for instance in order to corroborate the assumption of the cloud fraction being one of the ultimate control factors over the behaviour of East African lakes (Einevik 2009). Finally, the response of Lake Babati to a number of future climate change scenarios is tested and analysed to assess the flooding–derived risks in a near future.

More generally, the model developments presented here can also contribute to improved interpretation of proxy data of lake level and climatic changes retrieved from the lake sediments and covering around 3,000 years BP. They may also improve the predictions of the future behaviour of the lake making it possible to anticipate and better respond to flooding events.

1.2 Background

As early as in the beginning of the twentieth century, scientists studying climatic changes realised the importance of East African Lakes (Leakey 1931). Raised beaches around some lakes and old low–level moraines provided strong evidence of significantly different climatic conditions in a geologically recent time. Since then, many other studies have discovered geological records of climatic fluctuations in different lakes covering a range of time scales and periods (Nicholson 2000; Ryner et al. 2007; Ryner et al. 2008). The understanding of such records has thus been recognized to be a very important asset to comprehend the past climatic variability in the tropical areas. Additionally, combining the records from these different lakes can also provide
highly valuable information on the environmental evolution of East Africa (Yin & Nicholson 1998). However, even if much work has been done over the past century, there is still a large uncertainty concerning the chronology and extent of most past climatic events (Ryner et al. 2007).

Over the past millennium East Africa has experienced a series of spatial and temporal climatic changes involving significant rainfall variability (Ryner et al. 2008; Verschuren et al. 2000). The main factors driving the climatology of this area include El Niño – Southern Oscillation (ENSO) and the Inter Tropical Convergence Zone (ITCZ) (Russell & Johnson 2007). More recently the influence of the Indian Ocean Dipole has also gained attention (Marchant et al. 2006). Yet, the spatial and temporal extent of the cycles related to these phenomena is still not well understood (Ryner et al. 2008).

During the last century instrumentation of large areas of East Africa has allowed for the tracing of the circulation mechanisms responsible for the annual hydrological cycles and the climatic variability (Hastenrath 2001). Nowadays, water balance models are one of the most widely used tools to further understand the nature of the hydrological systems and to provide information about the effects of human related practices in the environment. Furthermore, they can also be used to test the sensitivity of the different parameters and ascertain the response of the system under different climate change scenarios.

### 1.2.1 Modelling East African lakes

Several attempts have been made to quantify the past and future evolution of a number of East African lakes. The approaches used differ from case to case depending on the objectives of the authors. Some relevant studies that may be useful for this work are presented in this section.

Lake Naivasha is a fresh water lake located in Kenya’s side of the East African Rift Valley which has no surface outlet. Hence, the lake’s water budget was calculated to successfully test the hypothesis of the existence of an underground outlet from the lake (Åse 1987). The influence of certain aquatic plant species to the evapotranspiration from the lake was also tested in the study.

Similarly, several attempts have been made to calculate the water balance of Lake Victoria. Yin and Nicholson (1998) developed a fairly good approximation of its water budget by assessing the lake rainfall both from meteorological stations and satellite
estimates. After studying the sensitivity of the parameters used by their model they pointed out the cloudiness to be one of the most important factors controlling the evaporation over the lake. Another study including several East African Lakes (Hastenrath & Kutzbach 1983) had already concluded that changes in the albedo, Bowen ratio and cloudiness were more likely to induce a water budget change than other parameters like temperature variations.

Ethiopian Lake Tana was investigated by Kebede et al. (2006) to estimate the sensitivity of its water level to different climatic parameters as well as to human impact. A water balance model was applied and supported the observations of the lake levels being rather insensitive to changes in rainfall or to human forcing.

In a study of particular relevance Sandström (1995a) developed a water balance model for Lake Babati. In that case, the water balance model was intended to simulate daily lake levels and flood discharge based on values of daily rainfall, surface and groundwater in- and outflows, groundwater storage and evapotranspiration. The main objective was to test the theory that flooding events in Babati were more likely to happen in deforested, degraded conditions rather than in forested, non–degraded conditions. The model presented a semi–lumped structure differentiating between the catchment area, the alluvial aquifer and the lake and the water balance equation was solved by considering a relatively large number of hydrological subsystems yielding however also a need for a relatively large number of input parameters.

Finally, some studies focus their attention to certain aspects of the water cycle in order to gain more detailed understanding of certain hydrological processes. A good example of this perspective applied to the study area is the simulation of the influence of precipitation variability on groundwater recharge in the Harra watershed in Tanzania (Sandström 1995b). The author found a significant decrease in groundwater recharge under deforested conditions when compared to a previous forested environment due to the closing of the soil macropores. The importance of this discovery lies in evidencing that human activities like deforestation may lead to an increase in flooding events rate and magnitude. A similar study with comparable results was also performed in south–western Australia (Ruprecht & Stoneman 1993).
1.2.2 Water balance model choice

For the present study the model developed by Sandström (1995a) was discarded due to the need of a large number of input parameters, whose values could not be correctly ascertained. A water balance model developed by Einevik (2009) for simulating lake level changes in Lake Emakat was considered as a suitable starting point instead.

Lake Emakat is located in Empakaai crater, around 150 km to the north of Lake Babati. The two lakes present many similarities but also some important differences and a good comprehension of those is crucial for a correct application of the model in Lake Babati. The most important resemblances consist in a relative close geographic position and a similar behaviour of the lakes levels. The second factor is really important as most commercial hydrological models are not able to simulate lake level changes. On the contrary, while Lake Emakat is a crater lake with a completely closed hydrological system and a small catchment compared to the size of the lake, Lake Babati has a big catchment and has been reported to overflow when the lake levels are high, opening its hydrological system. Therefore, in order to correctly simulate the behaviour of Lake Babati, some modifications need to be performed in the model’s design, mainly in the routines dealing with the catchment and the groundwater reservoir.

1.3 Site description

Lake Babati is located in northern Tanzania, at approximately 35°45’E and 4°15’S (Figure 1) and is one out of a chain of fresh water lakes extending across the East African Rift Valley (Kahurananga 1992). It is notably characterised by relatively shallow and fluctuating water levels, which can be related to changing climatology and precipitation (Strömquist & Johansson 1990). Other examples of lakes with similar features are Lake Manyara in Tanzania and Lake Naivasha in Kenya, the later having fluctuated up to ten meters during the last century (Strömquist & Johansson 1990).

Due to its fresh water and its shallow levels, Lake Babati supports a diverse ecosystem holding between seventy and ninety hippos and several species of lake birds (Kahurananga 1992). Additionally, Lake Babati is a favourable habitat for many fish species due to its clear waters and a strong seasonal nutrient inflow (Strömquist & Johansson 1990). This allows for many local people to make a living as fishermen and fishmongers (Kahurananga 1992). Babati Catchment also supports a rich and diverse wildlife consisting of a variety of game animals and birds. Due to the value of its
ecosystem Lake Babati is a protected habitat by legislation which is mainly aimed at being a hippo reserve. Despite this legal status, the protected areas around the lake have been reduced with time and administrative changes have made it difficult to stop some people from breaking the laws (Strömquist & Johansson 1990).

Figure 1 Location of Lake Babati. Modified from Sansdström (1995a) and Ryner et al. (2007).

1.3.1 Lake Babati Formation

In a geological time scale there is evidence that the East African Rift Valley lakes occupied larger areas in the past (Strömquist & Johansson 1990). Fossil shorelines and lake beds can, for example, be used to trace the past extent of Lake Manyara. Similarly, large extents of alluvial clays, silt and sands indicate the possible past extent of Lake Babati and its sedimentation basin. Huge areas of lacustrine sediments to the south of Dodoma also indicate the probable existence of an ancient lake covering that area (Strömquist & Johansson 1978).

Lake Babati is thought to have been formed in a similar way as Lake Manyara or Lake Burungi (Gerdén et al. 1992). According to the authors, both lakes might initially have been a part of a single, larger lake located within a catchment with internal drainage. At some point the Rift Valley floor began to uplift near the area of the proto–lake making the streams feeding the lake to slow or reverse. The energy decrease associated with
slower flows led to the dropping of the sediment loads and the creation of both temporary and permanent lakes in different valleys. One of these lakes is the present day Lake Babati. Tectonic instability in the area has far from stopped and continues to reshape the East African Rift. However, the extent of its effect to Lake Babati is unknown (Gerdén et al. 1992).

1.3.2 Lake Babati Catchment

Lake Babati catchment (Figure 2) covers around 355 km$^2$ and can be geologically and geomorphically subdivided in two different areas (Strömquist & Johansson 1990). The southern area consists of a steep landscape with hills and plateaux formed by Precambrian basement rocks. When approaching the lake the hills leave their place to wide plains of mbugas – seasonally flooded grasslands consisting of clay deposits – and clear sands. Large sand–fans are observed upstream from the mbugas. The two types of sedimentary deposits combine to create a large water infiltration area covering approximately 50 km$^2$ (Figure 2). On the contrary, in the northern area a volcanic landscape dominates. Neogene volcanic deposits in the shape of pyroclastics and minor explosion vents and craters form the major features. Similarly to the southern part of the catchment, mbugas and sands also surround the lake but in a minor extent. Large scale gully erosion takes place in the volcanic soils forming a well–developed drainage system that transports sediments into the alluvial sands and mbugas around the lake.

Babati town, which is situated at the northern edge of the lake, is located on a volcanic tuff ridge with dark brown soils which is highly erodible and susceptible to infiltration. Groundwater flow from the lake has been observed through this feature and to the valley to the east of the town where bananas, mango and citrus are cultivated (Strömquist & Johansson 1990).
1.3.3 Hydrology

The present day surface outlet of the lake is across the Great North Road, approximately 500 m to the south of the Singida Junction (Strömquist & Johansson 1990) (Figure 3). It is an artificial outlet which was constructed after a major flooding event in 1964 and which connects the lake to the Mrara gully system. The outlet was designed to be 366 m long and consisted of seven culverts capable of discharging up to 2 m³/s each, but with an estimated total capacity of 16 m³/s. After the 1990 flooding event the artificial outlet was redesigned. The overflow level was lowered, thirteen large culverts capable of discharging 4 m³/s were installed and the grass blocking the outlet was removed (Gerdén et al. 1992). A complete rehabilitation of the outlet was scheduled for autumn.
2010 consisting in the replacement of the round culverts by a box system that would allow for a greater capacity (Sjödin 2010). However, no information could be found to confirm the completion of the project.

Before the construction of the artificial outlet, this area used to be a deposition zone for sediments transported from the higher lands. Apart from the artificial outlet, there is no other natural well–developed outlet from the lake and the downstream drainage system is poorly developed. This is attributed to the fact that the run–off from the lake might have been somewhat erratic during the past. However, although alluvial deposits and channel–like features indicate that previous extreme floods may have passed through the town area, it is probable that drainage occurred mainly through the area where the artificial outlet is located. (Strömquist & Johansson 1990).

Several springs exist around the lake due to infiltration from higher grounds inside the basement complex. Concretely, most streams of the southern area present a steady groundwater base flow during wet conditions (Strömquist & Johansson 1990). Moreover, according to the same authors, the vegetation covered mbugas can act as an efficient sediment trap allowing for a large sedimentation rate in those areas. As a consequence, they calculate that more than 90% of the surface discharge water infiltrates consequently not reaching the lake.
Figure 3 Babati town and the major drainage routes during the 1990 flooding event. A – artificial outlet from the lake; B – part of the town constructed on ancient lake beds; C – main drainage course through the town. Modified from Strömquist & Johansson (1990).
1.3.4 Climatology

Together with a large part of Tanzania, Lake Babati Catchment is placed in the “Aw zone” according to Köppen’s climatological classification (Simonsson 2001). This means that this area has a tropical rainy climate with temperatures higher than 18 °C in the coldest month of the year.

More precisely the climate in Babati is mainly characterised by a rainy season lasting roughly from October to May and a dry season comprising the rest of the year (Strömquist & Johansson 1990). This pattern is produced by the movements of the Inter Tropical Convergence Zone (ITCZ) along the equator (Simonsson 2001). Between June and September, the prevailing high pressures and steady south–eastern winds keep the ITCZ north of the equator producing dry weather over Babati. Conversely, from October to May the presence of the ITCZ generates unstable weather conditions with irregular precipitation patterns. The rainy season can be further subdivided in what is commonly referred to as the “short rains” – from October to January – and the “long rains” – between February and May – (Simonsson 2001). Between the two rain periods there is a short and unreliable drier period (Newman & Rönnberg 1992).

Babati climate is also characterised by large inter–annual fluctuations in precipitation (Sandström 1995a). Such irregularity is thought to have an influence on the recharge rate of the groundwater aquifers and thus to eventually foster fast flooding events.

1.3.5 Land–use changes

The African continent has been inhabited by humans during thousands of years and there is evidence that the lands surrounding Babati have been used as grazing lands at least since 2000 years ago (Koponen 1988). Gullies more than ten meters deep testify extreme soil erosion episodes resulting from overgrazing. These features show that profound landscape changes were already being produced by early human populations (Simonsson 2001).

However, according to Strömquist (1992) and Sandström (1995a), at the beginning of the twentieth century the area was mostly largely uninhabited and covered by forests, and agriculture was only practiced in a fraction of Babati Catchment. Such dramatic change may be partly explained by a rinderpest event that took place at the end of the nineteenth century. That episode triggered the propagation of the tsetse fly, which was induced by the spread of a certain type of bushes in previous grazing land. The two
phenomena combined are thought to effectively have depopulated the area (Simonsson 2001).

During the twentieth century the situation changed drastically. In the 1940s and 50s the establishment of colonial states under the British administration led to a widespread cutting of the woodlands to prevent tsetse derived diseases and by the end of the 50s the area was opened up for immigration. The fertile land of Lake Babati catchment and its over–the–average annual rainfall attracted settlers who started large–scale cultivation of the land. Already in the 1970 most lake-side forests had been reduced significantly (Strömquist & Johansson 1990). Although forest clearance was stimulated to prevent tsetse fly from spreading, there was also some concern about soil erosion and a series of actions such as gully control, contour ridging of cultivated land or reforestation were taken by the British administration. However, some of these measures clashed with the tsetse preventing policies rendering some of these actions meaningless (Simonsson 2001).

During the 1970s the deforestation process continued to accelerate even further due to the large amount of people that had moved to the area during the 1960s. Most areas were converted into farmlands during that period in a process called villagization (Sandström 1995a). The local people interviewed by the author described the present–day landscape as jangwa, which is the local word for poor, dry soils with not many trees that are being overgrazed. There are also concerns of environmental damage caused by chemical pollution derived from mechanized farming in the uplands (Yanda & Madulu 2005). According to Newman & Rönnberg (1992), in 1960 there was still more bushland or woodland than cultivated areas while in 1990 the cultivated areas doubled the bushland and woodlands combined.

The importance of the land–use changes lies in the effect it has to the groundwater recharge. According to Sandström (1995b), who studied this issue in northern Tanzania, the degradation of a forested area in semi–arid climates leads to the closing of the macropores of the soil (see section 1.2.1). Macropores are crucial in these regions because they account for an important fraction of the groundwater recharge. Thus, the degradation of the ecosystems may lead to a decrease of the water recharge rate to the soil and consequently to an increase of the surface run–off that may eventually evolve into flooding (Perrolf & Sandström 1995).
1.4 **Meteorological and hydrological records**

During the last century people living in Babati have suffered from a changing climate and have witnessed several major flooding events, some of them putting in danger the village itself. To illustrate these events and their climatic and hydrological context the temperature and precipitation records and a brief description of the major flooding events, as well as a small account of the work done in a field trip in 2009 are presented in this section.

**1.4.1 20th century floods and lake level records**

During the last century there have been at least three documented major flooding events (Sandström 1995a). The first of these major events occurred in 1964 and the lake overflowed through the town area as well as the normal outlet destroying several houses in its path. The following major flooding event occurred in 1979. The town area was flooded again but unlike the 1964 event, the high rainfall accumulation in the area produced the high water levels to persist for a longer time.

In 1989 the lake levels were already high and by the end of the 1990 rainy season the town was flooded again despite of the opening of a new outlet at the Singida road junction. The Babati town main street suffered of intense gully erosion. Unlike previous events, high lake levels persisted throughout the subsequent dry season. The effects of this event were higher than expected for the amount of precipitation that fell during that period due to the fact that 75% of the area between the outlet and the lake was covered by vegetation, consequently obstructing the water discharge through the culverts (Gerdén et al. 1992).

Figure 4 shows the previously described flooding events related to the precipitation data from different neighbouring meteorological stations. Note that even though high rainfall peaks are found in the first half of the 20th century, there only exist a few references from this period.
Additionally, Simonsson (2001) mentions flooding events during 1997–1998 and also in 1919. However, due to the impossibility of retrieving more accurate data, the extent and importance of these events are unknown. In a more recent study, Sjödin (2010) also reports a flooding event in 2006.

After the flooding event of 1964 a gauge station (gauging station 2H15) was placed at the headland between the two bays at the north end of the lake to monitor the evolution of the lake level (Strömquist & Johansson 1990). The same authors also report the gauge base level to be set at 1341.39 m.a.s.l. Thereafter a series of lake water levels were recorded. However, the data series are fractionate due to some incidents, i.e. flooding of the gauge or damaging of the station by hippopotamuses. An illustrative series of the lake level records is presented in Figure 5.

**Figure 4** Precipitation variations at different meteorological stations and recorded flooding events. From Strömquist (1992).

**Figure 5** Recorded lake levels in Lake Babati at the gauging station 2H15. Modified from Strömquist & Johansson (1990).
1.4.2 Precipitation records

Precipitation data exists for a number of meteorological stations around Babati area. Singu farm station has records from 1931 to 1960, Galappo Mission station from 1961 to 1965, from 1969 to 1970 and incomplete records between 1966 and 1968 and Babati town station from 1971 to the present (Strömquist & Johansson 1990). The mean annual rainfall for the different stations can be found in Table 1.

<table>
<thead>
<tr>
<th>Period</th>
<th>Mean annual rainfall [mm]</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1931 – 1940</td>
<td>(791)</td>
<td>Singu</td>
</tr>
<tr>
<td>1941 – 1950</td>
<td>729</td>
<td>Singu</td>
</tr>
<tr>
<td>1951 – 1960</td>
<td>(856)</td>
<td>Singu</td>
</tr>
<tr>
<td>1961 – 1970</td>
<td>(635)</td>
<td>Galappo</td>
</tr>
<tr>
<td>1971 – 1979</td>
<td>790</td>
<td>Babati</td>
</tr>
<tr>
<td>1981 – 1989</td>
<td>825</td>
<td>Babati</td>
</tr>
</tbody>
</table>

Sandström (1995a), performed statistical analyses to try to correlate precipitation data series from Babati to some stations located at the proximity of the lake, i.e. Kondoa, Farkwa, Singida, Galappo and Dodoma meteorological stations. The selection of the stations was made on the basis of the locations presenting similar rainfall fluctuations as Babati station. The results obtained from multiple regression analyses were mainly positive although some coefficients of determination were not as high as expected.

1.4.3 Temperature records

Although a meteorological station has existed in Babati town for more than three decades and precipitation records exist for this period, temperature records are much more recent, being only two to three years old (Sjödin 2010; Tanzania Meteorological Agency 2008 pers. comm.). Unfortunately, these records were impossible to retrieve in time for this project.

Bibliographical studies show almost no references to temperature data except for the mean altitude dependant average temperatures reported by Simonsson (2001), which are shown in Table 2. Unfortunately, there is no mention of the source or the accuracy of the data and nothing is said about the measurement period.
Table 2 Elevation–dependent average temperatures for Babati area. Modified from Simonsson (2001).

<table>
<thead>
<tr>
<th>Elevation [m.a.s.l.]</th>
<th>Average temperature [ºC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 – 1000</td>
<td>22 – 24</td>
</tr>
<tr>
<td>1200 – 1500</td>
<td>18 – 20</td>
</tr>
</tbody>
</table>

On the other hand no lake water temperature records exist with the exception of some measurements made by Strömquist & Johansson (1990). Those measurements comprise temperatures at different parts of the lake but are restricted to the month of August.

### 1.5 2009 expedition

In July 2009 an expedition to Lake Babati was organised by Stockholm University to collect relevant data to improve the knowledge of the past evolution of East African Lakes. The crew, composed by Jerker Jarsjö, Maria Ryner and Jan Risberg, had as one of the main objectives to retrieve sediment cores from the lake that would be used to reconstruct the environment and climatology of the last c. 3000 years. During the expedition other data was also recovered. Among other things, several bathymetric profiles were done along the lake (data enclosed in Annex C), GPS coordinates of reference points were taken and detailed monthly rainfall data from several stations was collected.
2. Methodology

In order to be able to correctly reconstruct and represent the Lake Babati level changes a number of steps needed to be taken. For this purpose the area–volume relationship of Lake Babati was estimated and the water balance model of Einevik (2009) was modified to take into account the key features of Babati system. This section describes the processes followed to modify the model and prepare necessary input data to perform the simulations.

2.1 Overview of the Area–volume relationship derivation

The water balance model chosen to be used for this study has the particularity of needing an area–volume relationship of the considered catchment. This means that a number of possible lake areas and their corresponding lake volumes need to be retrieved. For this purpose a special program was designed by Einevik (2009) using FORTRAN 95. That program requires an input consisting in a digital matrix of the bathymetry/topography of the lake, from its bottom to its maximum possible size. The program then calculates a number of area–volume relationships at the chosen resolution. The output file can then be used as input to the water balance model.

2.2 Overview of the water balance model

The model developed by Einevik (2009) was designed with a lumped structure allowing for a simplification of the catchment into two different modules, i.e. the lake and the groundwater reservoir of the lake catchment. The model was aimed to solve a water balance equation and give the lake volume and associated lake surface area for a certain time from several meteorological parameters and allowed performing both steady state and time depending simulations. A choice about the groundwater reservoir shape was given and the groundwater level was forced to match that of the lake after every time step. The previously mentioned water balance equation takes the following shape:

$$\Delta V + \Delta V_r = \frac{1}{\rho_w} \left( PA_l + PA_r - E_l A_l - E_r A_r - R_f \right) \Delta t$$

(1)

Where $\Delta V$ is the change in the lake volume, $\Delta V_r$ the change in the groundwater volume, $\rho_w$ the water density, $P$ the precipitation, $A_l$ the area of the lake, $A_r$ the area of the groundwater aquifer, $E_l$ the evaporation over the lake, $E_r$ the actual evapotranspiration over the groundwater aquifer, $R_f$ the possible runoff from the lake and $\Delta t$ the time step.
The main particularity of the model is that the areas of both the lake and the nearby aquifer were designed to change with a changing lake volume. For instance an area-volume relationship was derived to allow for this purpose. Thus, an increase in the lake volume would lead to an increase of the lake area and a subsequent reduction of the aquifer area. Conversely, a decrease in the lake volume would produce the inverse effect. The ability to change the areas of the lake and of its groundwater reservoir makes this water balance model a powerful tool for the correct simulation of lake systems with large level fluctuations.

The necessary input data for the model includes the initial lake and groundwater reservoir volumes, the chosen groundwater parameterization, climatological data (temperature, precipitation, surface pressure, shortwave solar radiation, cloud fraction and relative humidity) and the lake area-volume relationship. The evaporation over the lake and evapotranspiration over the ground are calculated by the model through empirical equations and the longwave radiation can be calculated with two different equations. The program then solves the water balance equation for each time step until the predetermined number of time steps is over or otherwise until the volume change is smaller than a given convergence value.

2.3 Lake Emakat water balance model improvement

Once the structure of the water balance model was understood, the next step was to modify its FORTRAN 95 code to better fit the study purposes. Although the model was consistent and well–designed some changes needed to be performed due to the different characteristics between the previously considered Lake Emakat study site and the presently considered Babati catchment. The most important changes were related to the groundwater routine and the inclusion of the parts of the catchment outside the groundwater reservoir, which are the most outstanding difference between the two lakes (see section 1.2.1.1).

2.3.1 Ground evapotranspiration calculations

As previously mentioned, the water balance model developed by Einevik (2009) consists in two different modules: the lake and the groundwater reservoir of the lake catchment. This simplification works well for the catchment he studied as the steep walls of the Empakaai Crater place the water divide just at the edge of the groundwater reservoir. However, unlike Lake Emakat, Lake Babati has a big catchment compared to
the size of the lake. Thus, the rest of the catchment had to be included in the model as a new module in order to develop an accurate water balance model.

For this purpose, the area of the whole catchment ($A_{tot}$) as well as the combined area of the lake and its adjacent reservoir ($A_{rl}$) needed to be measured. Then the area of the rest of the catchment ($A_c$) could be calculated with the following relation:

$$A_c = A_{tot} - A_{rl} \tag{2}$$

Similarly, by combining $A_{rl}$ with the area of the lake ($A_l$), which can be retrieved from the lake area–volume relationship, one can easily derive the area covered by the groundwater reservoir ($A_r$) by the following relation:

$$A_r = A_{rl} - A_l \tag{3}$$

It has to be noted that, as mentioned in section 2.2, the values of $A_l$ and $A_r$ are allowed to change in every time step, modifying the total precipitation and evaporation/evapotranspiration volumes over the lake and its groundwater reservoir respectively.

Following the calculation of $A_c$ the expressions for the total precipitation and evapotranspiration over the rest of the catchment could be derived from those of the groundwater reservoir. The water balance equation could then be complemented with the precipitation and evapotranspiration factors for the rest of the catchment as follows:

$$\Delta V + \Delta V_r = \frac{1}{P_w} (P A_l + PA_r + PA_c - E_l A_l - E_r A_r - E_c A_c - R_f) \Delta t \tag{4}$$

Where $E_c$ represents the actual evapotranspiration over the rest of the catchment and it is expressed in [mm/year].

The actual evapotranspiration calculations for the reservoir and for the rest of the catchment were then slightly modified by including an empirical calibration factor, $X_{cal}$, allowing for a catchment dependant adjustment of the calculated evaporation from the empirical equation used by the model (Turc 1954). This calibration factor was introduced to adjust for the uncertainty of the evapotranspiration calculation over the catchment area (Jarsjö et al. 2008). Turc’s equation is thereafter expressed as follows for both $E_r$ and $E_c$: 
\[ E_a = X_{cal} \cdot \frac{P}{\sqrt{0.9 + \frac{P^2}{E_p^2}}} \]  

(5)

Where \( E_a \) is the actual evapotranspiration and \( E_p \) is the potential evapotranspiration, both in [mm/year].

### 2.3.2 Groundwater routine modifications

The main modifications made to the model were aimed to improve the groundwater routine. The more complex shape and larger volume of the reservoir in Lake Babati makes groundwater more influential on the Lake Babati water balance than it was for Lake Emakat. This effect is mainly perceived in the storage capacity of the aquifer and its change through time, which strongly influences transient state simulations.

However, due to the little data available, efforts were also made to simplify the simulation of the water storage in the aquifer. For this purpose two different lake level elevations (\( Z_{l,1} \) and \( Z_{l,2} \)) and their correspondent area average groundwater levels in the adjacent groundwater aquifer (\( Z_{r,1} \) and \( Z_{r,2} \)) were defined (all the values in m.a.s.l.). Figure 6 shows a cross–section of central Babati Catchment where the previously defined parameters are presented.

As the objective of the project is to simulate lake level changes, elevations below the lake dry–out level were not considered by the model. Therefore the previous elevations were transformed by the model to levels relative to the minimum elevation of the lake, \( D_{l,\text{min}} \) which was defined as a 0 m elevation. The resulting variables were termed \( D_{l,1} \), \( D_{l,2} \), \( D_{r,1} \) and \( D_{r,2} \) respectively. From these values, and using the previously obtained lake area–volume relationship to obtain the lake level at a certain time (\( D_{l,t} \)), the average groundwater level at that time (\( D_{r,t} \)) could be ascertained through a linear relationship as follows:

\[ D_{r,t} = D_{l,t} \cdot \left( \frac{D_{r,2} - D_{r,1}}{D_{l,2} - D_{l,1}} \right) + D_{r,\text{min}} \]  

(6)

Where all the values are in meters and \( D_{r,\text{min}} \) represents the area average groundwater level when the lake has dried out and it can be calculated using the following equation:

\[ D_{r,\text{min}} = D_{r,2} - D_{l,2} \left( \frac{D_{r,2} - D_{r,1}}{D_{l,2} - D_{l,1}} \right) \]  

(7)
This previous relationship (Equation (6)) could however lead to some simulation errors. One possible case is that, depending on the selected lake and groundwater elevation values, the extrapolated groundwater levels would eventually become higher than the ground surface elevation. Even though, if the measurement points are accurately obtained and introduced to the model these issues unlikely to happen.

A more complex process was to find the volume of the groundwater reservoir. For this study a simple approach was taken allowing for a good approximation without losing simplicity. For this purpose the volume of the aquifer at a certain time was represented by an irregular prism whose base is the shape of the area delimited by the groundwater level within the aquifer and whose vertical edges have the value of the groundwater elevation from the reference height at that time \((D_{r,t})\). At this point, the volume of the lake obtained from the area–volume relationship could be subtracted from the total volume to get the soil volume.

However, as the shape of the aquifer changes in depth and extent between different parts of the catchment and even more between different catchments, the groundwater volume could easily be overestimated (Figure 6). To avoid making such mistake the shape of the aquifer below the surface needed to be parameterised. An average depth dependant volumetric percentage of water reservoir formations to be found below a groundwater reservoir area and to the reference elevation \((R_{D,t})\) was thus implemented. The model was set to use a linear relationship which required the setting–up of two new parameters. \(R_1\) and \(R_2\), which represent the percentage of water reservoir formations below the reservoir area when the lake levels are set at \(D_{l,1}\) and \(D_{l,2}\) respectively (Figure 6). \(R_{D,t}\) is described by the following equation:

\[
R_{D,t} = D_{r,t} \ast \frac{(R_2 - R_1)}{(D_{r,2} - D_{r,1})} + \left[ R_2 - D_{r,2} \ast \frac{(R_2 - R_1)}{(D_{r,2} - D_{r,1})} \right] \tag{8}
\]

One issue concerning Equation (8) is that depending on the values given to \(R_1\) and \(R_2\), it could give percentages of water reservoir formations to be found below a certain groundwater reservoir area greater than 100%, which is not possible. Therefore, a failsafe condition was implemented to the code to set the output value to be equal to 1 for such situation.

Additionally, the mean porosity of the aquifer \((\varphi)\) was required to correctly define the water volume inside the reservoir. Thereafter, the previously derived variables could be
related to find the volume of the reservoir at a certain time \( V_{r,t} \) through the following equation:

\[
V_{r,t} = \left[ A_{rl} \times (D_{r,t} - D_{r,min}) - V_l(D_{r,t}) + V_l(D_{r,min}) \right] \times R_{D,t} \times \varphi \quad (9)
\]

The previously derived groundwater reservoir volume and groundwater level were then used for the calculation of the water volume routed to the groundwater reservoir at every time step to keep the specified relationship between the lake level and the groundwater level.
Figure 6 North–South topographic profile of the central part of Babati Catchment. $Z_{l,1}$ and $Z_{l,2}$ represent the two different known lake levels, $Z_{r,1}$ and $Z_{r,2}$ the corresponding area average groundwater levels and $A_{r,l}$ the combined area of the reservoir and the catchment.
2.3.3 Other changes

Finally, other small changes were also implemented to improve the functionality of the program. These changes comprise the inclusion – and modification – of the necessary equations to calculate the atmospheric pressure at a reference elevation and a simplification of the calculation of the different temperatures required by the model.

The surface pressure was originally calculated by hand by Einevik (2009) and then introduced to the model to proceed with the calculations. However, in order to facilitate the calculations and simplify the use of the model in different catchments some efforts were made to introduce the necessary equations to the code.

Regarding the temperature calculations, the presence of a much larger catchment area made it necessary to be able to calculate the temperature values for the parts of the catchment outside the aquifer and lake area. The representative temperatures of the groundwater reservoir and of the rest of the catchment areas were then calculated at their respective mean altitudes. The method used was the same as the one used by Einevik (2009), i.e. the temperatures were derived from a known reference temperature using the standard atmosphere gradient of 0.6 K for every 100 meters. The same method was applied to the air temperature at the lake surface ($T_a$), which was ascertained at every time step for the calculated lake surface elevation to give an accurate estimate. The lake surface water temperature ($T_w$) was allowed to vary with the air temperature at the lake surface through a constant temperature difference between the two, as showed by the following equation:

$$T_w = T_a + \Delta T$$ (10)

Where all the terms are expressed in K and $\Delta T$ represents the temperature difference. The decision to make the lake surface water temperature vary with the air temperature at the lake surface was taken regarding the relatively shallow depth of the considered lake that implies a low heat storage value in the lake and thus a similar evolution of the air and water temperatures (Vallet-Coulomb et al. 2001).

Finally, and although the program was already well structured and explanations were available for all the steps taken, efforts were also made to further simplify and clarify some of the equations used in the model in order to facilitate its use for future investigations. Similarly, most constants that were previously introduced to the code as mere numbers where modified and their acronyms were introduced instead. This
decision was taken to make them more easily recognisable and facilitate any further use of the code.

## 2.4 Scenario analysis description

Once all the modifications were introduced to the code, the water balance model was to be tested for a number of different hydro–climatic scenarios. First of all the model was to be calibrated using a well–instrumented period that would allow testing the sensitivity of its different parameters. Then a number of possible future scenarios were assessed to predict the likely evolution of Lake Babati system. The IPCC 4th Assessment Report projections were considered as the basis to construct the possible future scenarios as the latest IPCC assessment is a reference for climate change and its consequences (IPCC 2007). This section presents the IPCC derived scenarios used in the present study.

The last IPCC report draws regional projections for temperature and precipitation evolution during the twenty first century (Christensen et al. 2007). Figure 7 shows the temperature and precipitation projections and the number of models that predict an increase in precipitation for the African continent. Through the graphs one can easily identify Babati area to expect an increase in temperature of about 2.5 to 3 ºC and an increase in precipitation of around 10 to 15 %. Moreover, although there is always a margin of error for all the forecasts, the precipitation increase projection is to be judged quite likely as 19/20 out of 21 models estimate it.

From these projections, four different scenarios were envisaged with all the possible end–value combinations of temperature and precipitation increases (Table 3) for the Lake Babati system to be tested against. Note that the temperature and precipitation change values were calculated for over a period of one hundred years (from 1980 – 1999 to 2080 – 2099). Thus the different scenarios were forced to linearly change the parameters until the prescribed values were reached within the 2080 – 2099 period.
Figure 7 IPCC 4th report forecasted temperature (top–left) and precipitation (top–right) changes between 1980 – 1999 and 2080 – 2099 for Africa. The bottom graph shows the number of models (out of 21) that projected increases in precipitation. Modified from Christensen et al. (2007).

The results derived from the application of these four scenarios to the Lake Babati calibrated water balance model may be an asset to successfully assess possible courses of action in order to prevent any likely future issues derived from Lake Babati changing levels and its derived flooding events.

Table 3 Scenarios drawn from the IPCC regional projections for Africa.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature increase [°C]</td>
<td>2.5</td>
<td>2.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Precipitation increase [%]</td>
<td>10</td>
<td>15</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>
3. Synthesis of input data and model calibration

Once the context and the objectives were clear and all the necessary modifications were introduced to the model, the input data needed to be retrieved. First of all, the area–volume relationship of Lake Babati was to be found. Afterwards, the different meteorological and hydrological variables for a chosen reference period needed to be determined. Upon successful determination of all the input data, the model could finally be calibrated. This section describes the process of determination of the different required input data.

3.1 Determination of the area–volume relationship

In order to successfully determine the area–volume relationship of Lake Babati, a number of steps needed to be taken. These steps are detailed in the following sections.

3.1.1 Digital Elevation Model

First of all, a Digital Elevation Model (DEM) of the part of the catchment that was susceptible of eventually becoming flooded needed to be produced. The available material to work with consisted of several topographic maps covering the whole Babati Lake catchment area, bathymetric measurements performed during the 2009 campaign, and the absolute elevation of the lake artificial outlet.

The available topographic source consisted in four adjacent maps that combined covered the whole catchment area at a 1:50000 scale with a vertical resolution of 50 feet. The maps were produced by the Directorate of Overseas Surveys for the Tanganyika Government in 1964 and they were derived from aerial photographs taken in 1958 and 1960. The absolute elevation of the lake surface on the map is unknown but it can be approximated to lie between 4400 and 4450 feet (roughly between 1341 and 1356 m.a.s.l.) through the observation of the adjacent contour lines.

The bathymetric data consists of a series of measurements performed along five different transects that cover the most significant features of the lake (see Annex C). GPS coordinates were established for each measurement point so they could be projected on a map. However, as the absolute elevation of the lake surface at that time could not be retrieved, the water depth measurements could not be directly translated to topographic elevations. However, some progress could be made as the 2009 campaign
crew pointed out that the lake level was around three meters below the artificial outlet which according to Strömquist & Johansson (1990) is located at 1346.4 m.a.s.l.

Once all the available data was put together the first step was to scan and merge the topographic maps, delineate the Lake Babati catchment and georeference it. The areas on the topographic maps outside Babati catchment were removed and the georeferencing was performed by identifying and overlapping several outstanding features from both the scanned topographic maps and a reference geographic database as well as with GPS coordinates of some reference points taken during the 2009 campaign, i.e. Singida junction in Figure 3.

At this stage it was considered if it was necessary to digitise the entire catchment or if a smaller part would prove to be enough for the purpose of the study. According to the topographic maps the flatter areas that the lake could have covered in past times (Gerdén et al. 1992) are mostly constrained below 4600 feet of elevation (approximately 1402 m.a.s.l.), which is far above the elevation of the present-day artificial lake outlet. Therefore, the value of 4600 feet was taken as the highest elevation considered for the DEM.

Once the Lake Babati catchment topographic map was constrained and georeferenced the bathymetry measurements were plotted based on their GPS coordinates. Even though the absolute elevation of the measured points was not known, an estimate was made based on the qualitative observations from the 2009 campaign. Thus, the elevation of the water surface at that time was set to be at 1342 m.a.s.l.. Then, all the points were given elevation values relative to this altitude.

Topographic lines as well as other relevant features like streams and the 1960 lake surface shape were then digitised (Figure 8). The streams are an important feature as they help making a hydrologically correct digital model. As for the 1960 lake surface, its elevation was derived by linear interpolation from the bathymetry points placed at one side and the other of the 1960 lake shore.

Thereafter, four raster models were calculated at different horizontal resolutions (2.5, 5, 10 and 50 meters) using topographic lines, bathymetry points and the 1960 lake surface contour as inputs. Upon visual inspection it was decided that a horizontal resolution 10 meters was the most suitable option as the results were sufficiently close to the 2.5 and 5 meters resolution models. Conversely, the 50 meters resolution raster model presented
an important number of imprecisions and was discarded. Figure 9 presents a 3D representation of the central part of the catchment. In this figure (as well as in Figure 8) the dark green areas include the most part of the sedimentary deposits which, as previously mentioned, may represent the extent of the lake in a remote past (see section 1.3.1).

Additionally, Figure 10 represents the detailed bathymetry of Lake Babati until the overflow level. Note the flat topography of the lake bottom, consistent with the high deposition amounts revealed by Strömquist & Johansson (1990) and the siltation processes described by Yanda & Madulu (2005)

Figure 8 Digital Elevation Model (DEM) of Babati Catchment.
3.1.2 Area–volume relationship

The selected raster model was then processed to obtain the lake area–volume relationship for the catchment. This was done using a modified version of a program developed by Einevik (2009). The program was originally designed to double the resolution of the input matrix and then calculate a specific number of area–volume relationships of the higher resolution matrix. However, the program was simplified for this project and the high resolution matrix routine was eliminated. This decision was taken on the basis that the resolution of the raster model matrix was already high enough and that this step would not add any relevant information for the modelling (see section 3.1.1).

As mentioned in the previous section the lowest and highest elevations of the raster model were carefully selected to cover all the possible lake levels, from the bottom of the catchment to the extent the lake might have covered in a remote past, represented by the vast flat sedimentation areas. However, these limits considered the most part of the area–volume relationships fall above of the twentieth century lake outlet level. Therefore, and due to the fact that the scope of the project is mainly to simulate recent lake level changes, the calculated area–volume relationships where deliberately limited to the range of possible lake levels (from the dry–out level to the present overflow
level). Nevertheless, to be on the safe side the range was extended up to ten meters above the present day outlet (Figure 10).

**Figure 10** Detail of Lake Babati bathymetry and immediate surroundings as simulated for the raster model. The topographic contours are represented approximately until the maximum elevation considered for the Area–volume relationship.

Once the area–volume relationship was obtained (Figure 11) the quality of the data was checked against reports of lake surface areas by Strömquist & Johansson (1990). The
authors calculated the areas based on aerial photographs retrieved at different years. Specifically, the reported surface of 18 Km\(^2\) at 1990 – one of the years with massive flooding events – combined with the flooding lake level elevation of 1347.54 m.a.s.l. (Gerdén et al. 1992) (Figure 10) was successfully simulated by the area–volume model.

![Figure 11 Area–volume ratio for Lake Babati. The dashed lines indicate the present day area–volume ratio.](image)

### 3.2 Estimation of meteorological and hydrological variables for the reference period

As previously mentioned, there are neither long nor high resolution meteorological and hydrological data series for Lake Babati catchment. Moreover, data is fragmented and although records from nearby meteorological stations have been correlated to produce estimates of the conditions in Babati (Sandström 1995a), the coefficients of determination are far from high in some cases.

Thus, after studying the different existing data series it was concluded that the period with the most available information to perform the calibration was the first half of the decade of the 1980s, after the 1979 flooding event. Therefore, the decision to calibrate the model against that period was taken. The estimation of the different meteorological and hydrological variables for that period is described in this section.
3.2.1 Meteorological variables

3.2.1.1 Precipitation

Mean annual precipitation is given by Strömquist & Johansson (1990) for a series of time periods and different stations (see section 1.4.2). More precisely the mean annual precipitation for the period of interest was reported to be 825 mm at Babati meteorological station. There is however no instrumental data on the spatial distribution of the precipitation along the catchment. Therefore, the reported value was applied to the whole surface. This assumption may however lead to an underestimation of the precipitation at the higher parts of the catchment (Ahrens 2007).

3.2.1.2 Temperature

There was some incertitude regarding the temperature data. Publications about Lake Babati catchment rarely reported any temperature information and efforts to get access to the existing data series from the Babati meteorological station proved unsuccessful (Ryner 2011 pers. comm.; Tanzania Meteorological Agency 2011 pers. comm.). Therefore, average values from Simonsson (2001) for the 1200–1500 m.a.s.l. range were used for this project (see section 1.4.3). However, due to the imprecise nature of the values, it was decided to use the average of the temperatures – 19 °C – for the average of the elevations – 1350 m.a.s.l. –. These temperature and elevation were used as reference values and the different temperatures were then calculated by the model relative to these values (see section 2.3.3).

As for the lake surface water temperature, the lack of relevant mean values – the values published by Strömquist & Johansson (1990) could not be used due to their limited temporal extension – made it impossible to ascertain any accurate values. Therefore, the lake surface temperature was considered to be equal to the air temperature at the lake surface elevation. This approximation had already been used for another shallow, freshwater lake in Ethiopia (Vallet-Coulomb et al. 2001). In that case it was considered that the shallowness of the lake and the small seasonal temperature variations could allow for neglecting the stored energy term in the lake energy balance without introducing a significant error in the evaporation calculation on an annual basis. Due to the similar characteristics of both lakes this approximation was also considered to be valid for Lake Babati.
3.2.1.3 Surface pressure

The surface pressure was calculated by the model for the reference elevation (1350 m.a.s.l.) using the equations given by Einevik (2009) (see section 2.3.3). The surface pressure was thus ascertained to be 868.9 hPa. Even though, and as already pointed out by Einevik (2009) the lack of virtual temperature values, the low latitude of Lake Babati and the disregarding of the lake level changes may introduce some imprecision to the surface pressure calculation, which is however considered to be minimal.

3.2.1.4 Solar radiation

The latitude of Lake Babati being less than three degrees to the south of Lake Victoria allowed the use of the same value of incoming solar radiation as the one used by Yin & Nicholson (1998). The value used for Lake Victoria was derived from the calculations made by Black et al. (1954) of monthly average incoming solar radiation at a horizontal plane at the top of the atmosphere. The value used for the present study was thus 411.8 W/m².

3.2.1.5 Evaporation and evapotranspiration

A potential evapotranspiration value of 1660 mm/year measured in Kondoa (120 Km to the south of Babati) by Ngana (1992) was assumed by Sandström (1995a) to be representative for Babati area. The author also stated that the potential evaporation over Lake Babati to be of the order of 20000 m³/day and the actual evapotranspiration from the aquifer to be 480 mm/year on average.

However, these values must be treated with caution. The location of Kondoa – almost 1º to the south of Babati – combined with the lack of information about the exact placement (elevation) or the method used make the correlation very delicate. Additionally, it is not clear how all the evaporation values were derived based on the data from Kondoa. These considerations make the reported data definitively uncertain.

Additionally, setting a unique evapotranspiration value would make it impossible to assess impacts of climate change to Lake Babati, which is one of the objectives of this study. Therefore, the different evaporation and evapotranspiration values were calculated by the water balance model based on the available meteorological data. Furthermore, the model allowed for a choice between two different equations to ascertain the outgoing long wave radiation and thus the evaporation over the lake. The
equation used by Kebede et al. (2006) for Lake Tana (Ethiopia) was the one chosen to be used in this study as its parameterisation better fitted the available site data.

### 3.2.1.6 Cloud fraction and humidity

The cloud fraction and humidity were the most difficult meteorological variables to ascertain because there is no published, site–specific information regarding these two parameters. From the bibliography it can be appreciated that the cloud fraction values are highly variable from one place to the other. A cloud fraction of around 0.65 was calculated for Lake Naivasha (Bergner, Trauth & Bookhagen 2003). Similarly, Yin & Nicholson (1998) estimated a value of 0.5 over Lake Victoria; Kebede et al. (2006) ascertained it to be 0.3 for Lake Tana and Einevik (2009) determined the cloud fraction over Lake Emakat to be 0.25. On their study of the paleoclimatology of different East African Lakes, Hastenrath & Kutzbach (1983) gave a value of 0.5 for all the studied lakes with the exception of Lake Turkana, which was given a value of 0.45. As the different studies were not conclusive, it was decided to give a rough estimate of the cloud fraction for Babati Catchment. A value of 0.40 was chosen taking in consideration the latitude, altitude and precipitation values.

With respect to the relative humidity, the same issue had to be faced. The bibliography does not provide relative humidity values that can be extrapolated or that can act as a reference point for Lake Babati. The only value – 65% – is given by Bergner et al. (2003) for Lake Naivasha, which also presented a higher cloud fraction. The relative humidity for Lake Babati was then set at a neutral value of 50%. Nevertheless, according to Einevik (Einevik 2009), this parameter is not affecting the output from the water balance model in a significant way so, upon sensitivity testing, a rough estimate is considered valid in this case.

### 3.2.2 Hydrological variables

#### 3.2.2.1 Lake Babati level

An average Lake Babati level for the considered period was derived from the gauge measurement records. Measurements exist from May 1978 to September 1984 (Figure 5). An average of the values from January 1980 to the end of the series was made and a mean Lake Babati level of 1347.15 m.a.s.l. was obtained. It has to be noted that this value is only fifty centimetres lower than the overflow lake level (see section 3.1.2)
3.2.2.2 Groundwater variables

The modification of the original water balance model implies that several groundwater parameters needed to be known in order to correctly represent the groundwater storage in the reservoir. As required for the model two reference points of groundwater level had to be selected to calculate the relation that represents the groundwater storage changes in the lake catchment (see section 2.3.2). As no measurements could be done at the time of the investigation, the groundwater values had to be estimated.

The only reference information available was the groundwater table being quite close to the surface (around three meters deep) at several wells during the 2009 field trip (Jarsjö 2011 pers. comm.). The first reference point was thus decided to be placed at the overflow level of the lake. From average land surface elevation over the aquifer area (Figure 6) and the information from the 2009 campaign the area–average groundwater levels in the reservoir could be approximated to be around 5 meters higher than the lake levels. Similarly, the percentage of reservoir formations to be found below the reservoir area was approximated to 70%. For the second reference point, the dry-out level of the lake was used. The corresponding area–average groundwater level was resolved to be also set 5 meters above the lake level (Figure 6) considering the same groundwater behaviour as for the previous point and the reservoir percentage was estimated to be 60%. Table 4 presents a summary of the different groundwater parameter values.

Table 4 Lake level and corresponding area-average groundwater level and reservoir percentage for the two different points required to define the groundwater storage.

<table>
<thead>
<tr>
<th>Point</th>
<th>Zₐ</th>
<th>Zᵣ</th>
<th>Rₒ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>1336</td>
<td>1341</td>
<td>0.6</td>
</tr>
<tr>
<td>Point 2</td>
<td>1347.55</td>
<td>1352.55</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The porosity of the groundwater reservoir also needed to be quantified. An average value needed to be ascertained for the whole groundwater reservoir. According to Strömquist & Johansson (1990) the Babati aquifer consists of sandy fans in the distant parts and mbugas (mainly consisting in clay deposits) in the proximal parts. According to Edwards et al. (1983) typical values for soil porosity in Africa are 0.25 – 0.50 for sands and 0.40 – 0.70 for clays. Therefore, an intermediate value of 0.40 was considered suitable for the model.
3.3 Calibration factor determination and convergence criterion

Once all the parameters were determined the model was calibrated using a single calibration factor that modified one of the most uncertain parameters in the model, i.e. the total evapotranspiration (ET) over the catchment area according to the methodology outlined in Jarsjö et al. (2008); see also section 2.3.1. As mentioned before the main output from the water balance model is the lake level. Thus, the uncalibrated ET calculated by the model was adjusted by a single calibration factor \( X_{\text{cal}} \) (Equation (5)) such that the model reproduced the expected lake level. The calibration factor was thus ascertained to be equal to 1.1087 which corresponds to a relatively low (10%) modification of the uncalibrated evapotranspiration.

Thereafter the model was run starting from initial volumes close to the overflow level and to the dry-out level respectively to assess the correct behaviour of the water balance model (Figure 12). The figure shows the convergence of the water balance model outputs for the two selected starting volumes until they stabilise at the expected lake level. As it is expected the model takes a slightly longer time to stabilise when the initial values are further from the equilibrium level.

![Figure 12](image-url) Detail of the convergence of the lake levels to the equilibrium state when running the water balance model from a close to the overflow level (red line) and from a close to dry-out level (blue line). The dashed line represents the equilibrium level. All the other parameters were kept at the equilibrium values.
To perform the convergence tests a small convergence criterion was input in order to get a clear picture of the evolution of the model. A volume change of 1 cm per year was regarded to be small enough to consider the lake to be stationary. Therefore the correspondent convergence criterion for a change of this magnitude was set for the scenario simulations. The volume change required to produce such a level change could be easily retrieved from the area–volume relationship and was rounded–up to 10000 m$^3$/year.

### 3.4 Model parameters values overview

The values discussed in the previous sections for the different parameters during the reference period are listed in Table 5. As it can be observed in the previous sections, the temporal resolution of the different input parameters is somewhat limited. Therefore, the calculations needed for the parameter sensitivity studies and for the scenario simulations were made on an annual basis.

**Table 5** Summary of the parameters values for the calibration period.

<table>
<thead>
<tr>
<th>Hydrological variables</th>
<th>Climatological variables</th>
<th>Other variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_l$</td>
<td>1336 m</td>
<td>Precipitation 825 mm</td>
</tr>
<tr>
<td>$Z_r$</td>
<td>1341 m</td>
<td>Temperature 19 °C</td>
</tr>
<tr>
<td>$R_D$</td>
<td>60%</td>
<td>Shortwave radiation 411.8 W/m$^2$</td>
</tr>
<tr>
<td>Point 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_l$</td>
<td>1347.55 m</td>
<td>Cloud fraction 40%</td>
</tr>
<tr>
<td>$Z_r$</td>
<td>1352.55 m</td>
<td>Relative humidity 50%</td>
</tr>
<tr>
<td>$R_D$</td>
<td>70%</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Lake level</td>
<td>1347.15 m</td>
<td></td>
</tr>
</tbody>
</table>
4. Model simulation results

Once the area–volume relationships as well as the meteorological and hydrological parameters were introduced to the model and the calibration factor was determined the model was ready for performing simulations in Lake Babati catchment. However, before the different scenarios could be introduced to the model, the sensitivity of the different parameters needed to be tested. The results of the sensitivity studies and the scenario analyses are presented in this section.

4.1 Sensitivity studies

For the sensitivity studies two different types of tests were performed. First the sensitivity of different relevant climatological parameters was tested and the change required in the parameters to produce an overflow and a dry–out of the lake was quantified. Then the lake level response to changes in the ambient conditions was tested by computing the time until one of the previously mentioned situations occurred considering an instant change of each of the considered parameters.

4.1.1 Parameter sensitivity

The sensitivity of four climatological parameters – temperature, precipitation, cloud fraction and relative humidity – was tested by changing one parameter at a time and analysing the changes produced to the lake level.

Figure 13 presents the evolution of the lake level as a function of the changes introduced to each of the parameters. The most outstanding feature of the sensitivity study results is the insensitivity of the lake level to the relative humidity. Secondly, it can be appreciated that the changes in precipitation and temperature produce an inverse effect in the lake level, i.e. a temperature increase produces a rapid lowering of the lake level while a precipitation increase produces a rising. Finally the model sensitivity to the cloud fraction presents a characteristic pattern; while a small increase in this parameter produces overflow, the lake would never dry–out by the sole effect of this variable.
The importance of the sensitivity studies lies in quantifying the change that would be needed in a certain parameter to produce extreme lake levels, namely dry–out (0 m depth in Figure 13) and overflow (11.55 m depth – dashed lines in Figure 13) situations. Thus the changes required for each parameter to produce one of the previously mentioned lake level extremes were calculated and presented in Table 6. Note that for both temperature and precipitation the changes required to produce dry–out are much larger than the changes needed to produce overflow. For instance, all other conditions being equal as in the calibrated model run representing current conditions, the temperature would need to increase from today’s 19 °C (dotted, vertical line) to 21.76 to produce a dry–out and decrease to 18.88 °C to produce an overflow (Figure 13a). Analogously, the precipitation would need to decrease from the current 825 mm/year to 728 mm/year to produce a dry–out, and increase to 830 mm/year to produce an...
overflow (Figure 13b). Finally, the cloud fraction would only need to increase from the current 40% to a 42.5% to produce an overflow situation.

Table 6 Changes in the parameters than produce overflow and dry–out of the lake. The parameters are changes one at a time, giving three different overflowing conditions and two different dry–out conditions. NP stands for Not Possible.

<table>
<thead>
<tr>
<th></th>
<th>Temperature change [ºC]</th>
<th>Precipitation change [mm]</th>
<th>Cloud fraction change [%]</th>
<th>Relative humidity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overflow</td>
<td>−0.12</td>
<td>5</td>
<td>2.5</td>
<td>NP</td>
</tr>
<tr>
<td>Dry–out</td>
<td>2.76</td>
<td>−97</td>
<td>NP</td>
<td>NP</td>
</tr>
</tbody>
</table>

4.1.2 Model lake level response to instant parameter changes

In addition to knowing the climate parameter values that may lead to an overflow or a dry–out situation it is important to know in which time scale these lake level responses to changed ambient conditions are likely to occur. Therefore, a new set of tests were performed to investigate how long would it take for the system to rebalance itself after an instant change of each of the parameters leading to a lake level close to the dry–out and to a lake level close to the overflow limit.

Figure 14 shows the evolution of Lake Babati system after applying the previously mentioned instant precipitation change. Even though the starting level is much closer to the overflow level the system takes less time in rebalancing in the dry–out case than in the overflow case. A difference in the lake level evolution for the different scenarios can also be appreciated. For the dry–out case there is a rapid level change until it achieves a value close to the equilibrium level. Then the model takes a long time to stabilise at the exact equilibrium level. On the other hand, for the overflow case the lake depth converges smoothly to the equilibrium level with time.
Figure 14 Lake Babati stabilisation times for instant precipitation changes leading to (a) dry–out and (b) overflow. The dashed line represents the overflow level.

The times required for the system to reach the new equilibrium situations for an instant change in temperature are presented in Figure 15. The situation is similar to the system evolution for an instant change in precipitation; the system also reaches the new equilibrium situation faster for the dry–out case than for the overflow case. Nevertheless some differences exist. In this case, for the dry–out case the model takes a shorter time to stabilise when the new equilibrium level is achieved. Similarly, for the overflow case the lake levels tend to converge to the equilibrium level slightly faster.

Figure 15 Lake Babati stabilisation times for instant temperature changes leading to (a) dry–out and (b) overflow. The dashed line represents the overflow level.

Finally the time required for the system to reach the new equilibrium situation was evaluated for an instant change in the cloud fraction (Figure 16). For this case there was only one possible case as it was not possible to produce a dry–out of the lake by an
instant change of this parameter. The response of the system to this parameter is quite similar to the response it had towards the precipitation. When comparing Figure 16 to Figure 14 one can appreciate that the shapes of the lake level evolution are practically identical.

![Lake depth vs time graph](image)

**Figure 16** Lake Babati stabilisation time for instant cloud fraction changes leading to overflow. The dashed line represents the overflow level.

### 4.2 Simulation results – future scenarios

Once the sensitivity studies were successfully performed the model was used to reproduce the Lake Babati response to the different scenarios drawn in section 2.4. As the model was calibrated for the prevailing conditions of the period between 1980 and 1985, the model was set to run for 100 years and the scenario dependant parameters were linearly changed until they reached the prescribed values at the end of the simulation, around 2080 – 2085. These changes are perfectly consistent with the projections made by Christensen et al. (2007).

Figure 17 shows the evolution of the lake depth for each of the four scenarios. At a first glance two different behaviours can be appreciated. Scenarios 2 and 4 produce an overflow of the lake after 11 years while Scenarios 1 and 3 take around 15 years to achieve this situation. Note that even though the lake response differs from one scenario to the other, the lake reaches the overflow level in less than 20 years in all the cases, which is a remarkably shorter time than the 100 years period considered by the climate change scenarios. Taking a closer look it can be observed that in Scenario 1 and 2 the lake level evolves faster than those in Scenarios 3 and 4. The different behaviours can be related to the definition of the scenarios. For Scenario 2 and 4 the precipitation
change was larger than for Scenarios 1 and 3. Similarly, the temperature change was larger for Scenarios 1 and 2 than for Scenarios 3 and 4 (see Table 3).

![Figure 17](image)

**Figure 17** Different Lake Babati evolution patterns responding to the scenarios projected from the IPCC 4th report.

The effective temperature and precipitation changes required for the lake to reach the overflow level in the different scenarios are presented in Table 7. Note that as the parameters were set to change linearly through the simulation time and as the lake reached the overflow level in much shorter times than considered for all the scenarios, the effective parameter changes are much smaller than the initially considered values.

**Table 7** Parameter changes required to increase the lake level to the overflow limit for the different IPCC derived scenarios.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
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<tr>
<td>Temperature increase [°C]</td>
<td>0.375</td>
<td>0.275</td>
<td>0.45</td>
<td>0.33</td>
</tr>
<tr>
<td>Precipitation increase [%]</td>
<td>1.5</td>
<td>1.1</td>
<td>2.25</td>
<td>1.65</td>
</tr>
</tbody>
</table>
5. Discussion and conclusions

This last section closes the project by presenting a detailed discussion of the results obtained as well as an evaluation of the methodology used and of the improvements made to the water balance model. The main conclusions derived from the present study are then drawn and a reflection on possible further studies is finally made.

5.1 Model uncertainty sources

In the process of modifying the water balance model developed by Einevik (2009) some calculations were changed but more importantly several new parameters were introduced. Einevik (2009) performed a series of tests to ascertain the sensitivity of the model to the most relevant parameters and also gave a qualitative approximation of the different possible sources of uncertainty. However, the modifications introduced to the model as well as the calibration for a catchment with different characteristics may modify the previous assumptions by improving some routines or otherwise by introducing new uncertainties.

One of the main sources of uncertainty of the modified water balance model is thought to be the new groundwater routine parameterisation. Even though this routine needed to be changed to accurately describe the groundwater processes in a larger catchment, the parameters chosen to describe it may also introduce some uncertainty. The main concern was the impossibility to carry out direct measurements and thus not being able to precisely ascertain the magnitude of these parameters. Therefore, the results of the transient simulations presented in this study (i.e. the time it takes for the lake to respond to changes in ambient conditions) must be taken with caution, as they are bound to some uncertainties derived from estimation of these different parameters. Although out of the scope of the present study this issue could be properly assessed by taking direct measurements of the water table at different representative locations of the groundwater reservoir and averaging the obtained values. This methodology should ideally be applied at least for two different lake level episodes, i.e. when the level is relatively high and when it is relatively low. However, for situations where such measuring campaign might be difficult to put in practice, a single set of measurement would suffice. The other point would then need to be extrapolated from the available data assuming a consistent behaviour of the groundwater.
Another parameter which might introduce some uncertainty to the water balance model results is the evapotranspiration (ET) over the ground. As already pointed out by Einevik (2009) for Lake Emakat, the lack of measurements such as the cloud fraction or the average wind speed impeded the use of a more accurate equation to quantify ET. The empirical equation used provides with a rough estimate of the evapotranspiration instead. The calibration factor described by Jarsjö et al. (2008) was then introduced for this study. This factor allowed for a small modification of the evaporation value over the lake and was an asset for the correct calibration of the water balance model for Lake Babati. Moreover, such a small correction supports the idea of a limited model uncertainty related to ET and enhances the confidence to the model simulation results.

Consequently, the knowledge of the possible uncertainty sources and their extent is important to understand the validity of the results here presented, in particular for the response–time results. However, as the aim of the present study was the water balance model development and improvement and its subsequent testing in Lake Babati catchment, a more detailed analysis of the uncertainties was beyond the scope of the project.

5.2 Sensitivity studies

The sensitivity studies are an important tool to understand the behaviour of the water balance model and to quantify the influence of different parameters to the system performance. In the present study the most relevant meteorological parameters as well as the time dimension of the model were the variables chosen to be analysed. The results obtained from the tests performed were interesting and thus they need to be discussed in detail.

As previously mentioned the relative humidity plays an almost irrelevant role in the Lake Babati water balance (see Figure 13d). This tendency was already pointed out by Einevik (2009) in his study of Lake Emakat where this parameter is described to have a small effect within a reasonable span of relative humidity. Moreover, the even smaller influence of the relative humidity in Lake Babati compared to Lake Emakat may be explained by the differences between the lake and their respective catchment sizes in the two systems. In the water balance model used for the two studies the relative humidity is only considered as a factor to calculate the evaporation over the lake. It is therefore reasonable to assume that the relative humidity will have a much smaller effect in the
modelled Lake Babati system as the catchment is much larger relative to the lake size. Hence, the present study further supports the small sensitivity of the water balance model to the relative humidity. Therefore, the neglecting of this parameter for Lake Babati catchment is considered not to be critical for the model behaviour.

Conversely, together with other authors (see section 3.2.1.6), Einevik (2009) also stated that the cloud fraction was the most important parameter driving the evaporation over the lake and thus, controlling lake level changes. The results obtained in this present study clearly support this theory. Figure 13c shows that a small increase in the cloud fraction could produce an overflowing situation. On the other side, the impossibility to trigger a dry–out of the lake by the sole effect of this parameter is regarded more as an effect of the size of the lake. This similarity is due to the fact that both the cloud fraction and the relative humidity are only considered in the calculation of the evaporation over the lake but not in the calculation of the evapotranspiration over the ground. So, even if a smaller cloud fraction increased the modelled evaporation over the lake, an evapotranspiration change over the catchment due to cloud fraction change could not be reproduced (due to model assumptions) although such an effect is possible in principle. One course of action to improve the response of the system to this parameter would be the use of evapotranspiration equations that take into account the cloud fraction. This step would however be of little use in locations where there is no cloud fraction data, such Lake Babati catchment.

The model sensitivity to temperature and precipitation changes (Figure 13a and Figure 13b, respectively) is also interesting. The system shows the expected evolution for each of the parameters, i.e. a decrease in temperature or an increase in precipitation producing overflow and the opposite producing dry–out. However an important result is that a temperature change of less than 3ºC or a precipitation change of around 100 mm/year would be more than enough to bring the lake from an overflowing situation to a dry–out situation. The sensitivity of the model to both parameters is therefore considered to be large.

Another remarkable feature is the shape of the lake level evolution curve for both precipitation and temperature. This curve is mainly due to the topography of Lake Babati catchment, with its characteristic flat bottom (see Figure 10). In both cases, for low lake levels a steep slope can be appreciated. This can be related to the area–volume ratio of the lake (Figure 11), where for small areas – and thus for low levels – the
volume of the lake is almost negligible. On a wider perspective, the lake depth change produced by the same change in temperature or precipitation is likely to be different for different initial conditions due to the irregular morphology of the topography.

The model response time for the instant parameter changes is also characteristic. The overflow and dry–out patterns are similar for the different parameters considered but yet some differences can be appreciated. Regarding the dry–out case, one could appreciate that even if the system reaches the equilibrium level quite fast (around 12 years for both temperature and precipitation changes) it takes quite a long time to stabilise itself. This is thought to be related to the area–volume ratio of the lake. As previously discussed the temperature/precipitation values required to maintain such low lake levels need to be very concise (at those levels a temperature difference of just 0.1 °C could make the lake level change by one meter). An important appreciation to make at this point is that for instance a one year long dry spell would not be enough to dry out the lake.

On the other hand, the responses of the system to the overflow case are completely different. Instead of a fast evolution of the lake level to sharply stabilise around the equilibrium level, the system tends to the equilibrium point in a much smoother way. Even though the exact equilibrium levels are not reached after 40 years in the case of precipitation and cloud fraction changes and in around 30 years in the case of temperature changes, after 15 years the system is lake is found to be at less of 5 cm from the equilibrium level for all the cases.

When the dry–out and the overflow cases are compared, it is clear that an eventual dry–out of the lake would occur much faster than an overflow for the all the selected instant parameter changes. One may however tend to think differently as the original lake level is set to be much closer to the overflow level than to the dry–out level. There are two main reasons that justify these apparently contradictory results. First, a larger change in one of the parameters will produce a larger response on the system than a small change, which will only produce a gradual rebalancing. Second, the bathymetry makes it more difficult for the lake to increase its depth than to reduce it. The larger area of the lake for deeper levels (see section 3.1.2) means that a larger water volume is required to continue rising the lake level. Conversely, for a decreasing lake level the volume needed to be subtracted from the lake gets smaller as the lake shrinks. It is however clear that, in all the cases, a relatively small change in the values of one of the key parameters would lead to an extreme situation in a mid–term.
5.3 Hydro–climatic scenarios studies

The future scenarios simulation results are perhaps the most interesting results obtained in this study. The IPCC predicts an increase in both temperature and precipitation in Lake Babati area and according to the sensitivity studies, changes in temperature like the ones portrayed in the different scenarios could lead the lake to a significant shrinking. Conversely, the considered precipitation changes would produce an overflow of the lake. Consequently, the changes considered in each of the parameters will have opposite effects to the system for all the considered scenarios. The sign and the extent of the lake level changes will thus point out the most influential parameter.

Figure 17 clearly shows an increase in the lake depth for all the four scenarios which inevitably leads to an overflow situation. Additionally, two main different tendencies can be appreciated between the different scenarios. The lake is simulated to overflow in 11 years for the scenarios including larger precipitation changes while the same situation would take 15 years to occur in the scenarios with lower precipitation changes. The temperature is also shown to have some effect, although to a minor extent as scenarios with a larger temperature increase present a somewhat slower evolution. From the behaviour of the different scenarios it could be extracted that the precipitation is the most influential parameter driving the Lake Babati system and that the temperature effect is almost negligible. This conclusion is consistent with the flooding events happening after particularly wet rainy seasons and with the high variability of the lake’s water levels being coupled with the intrinsic rainfall variability patterns over the region. In addition, the fact that the results were consistent for all the four scenarios derived from the IPCC 4th Assessment Report, further supports the robustness of the hypothesis.

The second important reflection deals with the time required for the lake to overflow under these scenarios. As previously mentioned the different scenarios are drawn directly from the IPCC 4th Assessment Report projections for Africa and the precipitation projections for this specific area were judged to be quite likely. This would mean that Lake Babati overflowing times for all the scenarios would be much shorter – 11 to 15 years – than the times considered for the IPCC scenarios – 100 years –. However, when dealing with this time spans one still has to consider the possible uncertainty derived from the disregarding of the probable cloud fraction change in these scenarios and from the groundwater parameterisation in the transient state simulations.
that would make these values to vary slightly. All things considered it seems likely that Lake Babati may overflow in a relatively short time.

Even though the previously considered hydro–climatic scenarios were found to be able to raise the mean levels of Lake Babati to the overflow level in a relatively short term, a further concern is that in a region with such irregular weather patterns and fast response times flooding events such the 1990 one could be triggered far before the simulated times for the different scenarios. For instance, when the lake is not at its full capacity, it can act as a buffer smoothing the response of the system to extreme precipitation events. However, if the mean lake levels are close or at the overflow limit the lake loses its buffering effect and any extreme precipitation event is routed directly to the outlet of the lake producing flooding. Additionally, if the conclusions drawn by Sandström (1995a) of flooding events being favoured by the environmental degradation of Babati catchment are also taken into account, the situation would be very dangerous for Babati town and its inhabitants. Therefore, if no preventive actions are taken the ridge in which it is asssented could eventually be damaged by flood–generated gully erosion which might lead to a permanently draining the entire lake (Strömquist & Johansson 1990).

5.4 Conclusions

Lake Babati is a lake characterised by its changing levels that are strongly influenced by precipitation changes. This behaviour has caused large flooding events in the past endangering both infrastructure and people and may cause further damage in a near future.

The modifications introduced in this study to the water balance model by Einevik (2009) successfully allowed for a correct calibration of the model for Lake Babati and the performance of further simulations even if the uncertainty introduced by some parameters needs to be further assessed.

In this work the precipitation was ascertained to be the main parameter driving the lake level changes in Lake Babati and the relative effects of the cloud fraction and the relative humidity previously mentioned in the bibliography were supported by the results.

The sensitivity studies revealed that climatic changes such as a temperature decrease of less than 3 °C or a precipitation increase of around 100 mm/year would be more than
enough to eventually bring Lake Babati from a dry–out situation to an overflow situation.

All the simulations based on the IPCC projections for Lake Babati showed that a rise of the average lake level until reaching the overflow limit is likely in the near future. This hypothesis was supported by the robustness of the model simulations and would also imply that prior to reaching the overflow limit, new flooding events could continue to damage the town and even permanently draining the lake. This scenario would be even further enhanced by the reduced buffering effect of Lake Babati to extreme precipitation events.

All considered, further studies need to be made in Lake Babati catchment to assess this likely future trend and if needed take the pertinent actions to prevent future flooding events to damage the town and its inhabitants as well as their way of life. Similarly, sustainable development policies should also be implemented to prevent mankind to further damaging the environment by transforming and degrading the land.

### 5.5 Future work

The methodology presented here is not intended to be limited to a certain catchment morphology or climatic and hydrological background but to be applicable in a range of different situations and time scales. Therefore it would be of great interest to further apply the here described method in different contexts to test its applicability. In this line of work the water balance model could be further improved to more precisely describe the hydrological processes involved in the water balance of a lake without losing its simplicity. A good starting point would be to quantify the uncertainties derived from the groundwater parameters.

Concerning Lake Babati, an interesting continuation of this study would be to test the robustness of the model, i.e. to further test the ascertained value of the calibration factor by importing another set of initial parameter values. The expected outcome for a robust model would be to obtain shifted overflow and dry–out figures but the same overall dynamics. Thereafter the model could contribute to improved interpretation of proxy data of lake level and climatic changes retrieved from the lake sediments during the 2009 campaign and covering around 3,000 years BP.
6. Acknowledgements

First of all I would like express my gratitude towards my supervisor Jerker Jarsjö for his enthusiasm and the uncountable hours of dedication and support throughout all the stages of this project. Similarly I would also like to thank my assistant supervisor Maria Ryner for her enthusiasm and her help in the data gathering and correction.

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### Long Transect

<table>
<thead>
<tr>
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