HYDROLOGICAL WATER BALANCE OF LAKE TANA, ETHIOPIA

[1]Yirgalem A. Chebud and [2]Assefa M. Melesse

[1]Department of Earth Sciences, Florida International University, USA
[2]Department of Environmental Studies, Florida International University, USA

ABSTRACT

The level of Lake Tana fluctuates annually and seasonally following the patterns of changes in precipitation. In this study, a mass balance approach is used to estimate the hydrological balance of the lake. Water influx from five major rivers, subsurface inflow from the flood plains, precipitation, outflow from the lake constituting river discharge and evapotranspiration from the lake is analyzed on a monthly and annual basis. Spatial interpolation of precipitation using rain gage data was conducted using kriging. Outflow from the lake was identified as the evaporation from the lake surface as well as discharge at the outlet where the Blue Nile commences. Groundwater inflow is estimated using MODFLOW Software that showed an aligned flow pattern to the river channels. The groundwater outflow is considered negligible based on the secondary sources that confirmed absence of lake water geochemical mixing outside of the basin. Evaporation is estimated using Penman, Meyer's and Thornwaite's methods to compare the mass balance and energy balance approaches. Meteorological data, satellite images and temperature perturbation simulations from Global Historical Climate Network (GHCN) of NOAA are employed for estimation of evaporation input parameters. The difference of the inflow and out flow was taken as storage in depth and compared with the measured water level fluctuations. The study has shown that the monthly and annually calculated lake level replicates the observed values with RMSE value of 0.17m and 0.15m, respectively.

Key Words: Lake Tana, Blue Nile River, water balance

INTRODUCTION

Lake Tana is located in the northwestern part of Ethiopia (Figure 1) and it has a surface area of 3156 km^2, which is 20% of the 16000 km^2 drainage area. The lake receives perennial flow from four rivers: Gilgel Abay, Rib, Gumera, and Megech contributing 93% of the inflow, and at the outlet starts the Blue Nile. Very few studies that target at sensitivity of the lake level through time with changes in climatic conditions have reported that the lake is less sensitive to rainfall variations showing 10% decrease in lake level despite 50% decrease in precipitation (Kebede et al., 2005). Apparently, such studies are based on lumped mass balance approaches. Two approaches of validation seem relevant to establish the hydrological water balance of Lake Tana. The first approach by Immerzeel (2007) is validation of the water balance from distributed hydrological modeling perspective. This approach has shown that the sensitivity of the inflow to precipitation, showing 32% decrease in runoff with 10% decrease in precipitation (CEEPA, 2006). This has shown that sensitivity of the water balance against precipitation is indirect through the runoff demanding a distributed hydrological model. The significance of sensitivity of the water budget to runoff given the seasonal distribution of rainfall is reported by Conway (1997). The second approach (Moreda et al., 2006) is to validate the components on lumped water balance. This approach is set to review water balance parameters and also estimate a lumped hydrological balance of Lake Tana. The rationale is to see the room for improvement of methods on input determination even before costly distributed hydrological models is employed.

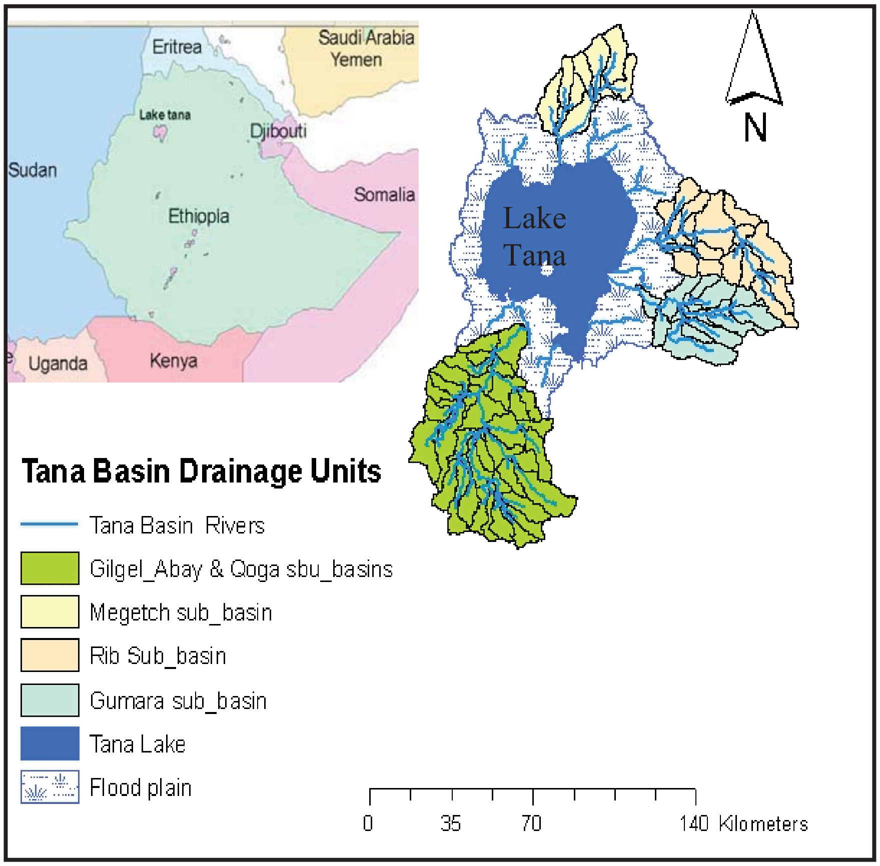

Figure 1. Tana basin, sub basins and the flood plain

Review on Water Balance Input Variables

Precipitation

Point measurement of precipitation and the increasing uncertainty on spatial distribution is a major problem for large scale hydrological studies. In recent years, the use of satellite images and estimation of perceptible water vis a vis determination of cold cloud duration index (CCD) is in the fine tuning process. Such studies conducted in the Blue Nile River basin have shown a correlation coefficient of 0.65 with the rain gauge measurements (El-Sebaie, 1997). This approach will have a significant role in understanding ungauged watersheds. On the other hand, the use of statistical down-scaling techniques, namely Kriging appear to be preferable for its incorporation of the data to generate an ensemble and interpolate or extrapolate the spatial estimates. The spatial regression of precipitation with latitude, longitude and altitude has worked well in the upper Blue Nile basin (Conway, 1997). These methods overweigh the traditional approach of Thiesson polygon and contouring techniques.

Evapotranspiration

Evapotranspiration is often estimated with the assumption of mass and energy balances or a combination of the two. Amongst these methods, the energy budget equation is reported to be reasonably appropriate for large scale studies (Melesse et al., 2006, Lee et al., 2000). The stability of the method is determined by the Bowen Ratio (BR) of the sensible heat flux against the heat used for evaporation and simplified as follows (Lee et al., 2000).

$$BR= 0.00061P(T_0 - T_a)/(e_0 - e_a) \quad (1)$$

Where P is barometric pressure, in millibars; T_0 is water-surface temperature, in degrees

Celsius; T_a is air temperature at 2 m above the lake in degrees Celsius; e_0 is saturation vapor pressure at the water-surface temperature in millibars; and e_a is vapor pressure at 2 m above the lake in millibars.

The ratio constrains the applicability between 0 – 1. While the negative value would mean no evaporation, large positive values suggest inclusion of mass balance. In the case of Lake Tana, the average lake surface temperature data is about 3^oC above the air temperature (Kebede et al., 2005) and the energy budget equations is applicable at all seasons. However, applicability of energy budget equation could be questionable in large lakes where turbulence production could overweigh the buoyancy for certain period. In such conditions, accounting the evaporation through mass transfer budgets could be acceptable.

The applicability is constrained by Stability parameter for Mass Transfer (*SMT)*, which is proportional to the Richardson number (Lee et al., 2000)

$$SMT = (T_h - T_0)/(u_h)^2 \qquad (2)$$

Where, T_h is temperature at height h, in degrees Celsius; T_o is temperature of the lake surface, in degrees Celsius; and u_h is wind speed at height h, in miles per hour.

When, *SMT* is high, the mass-transfer equation underestimates evaporation the (buoyant forces dominate) implying use of energy budget equation could be realistic. On the other hand, if SMT is low, the mass-transfer equation tends to overestimate evaporation (turbulent forces dominate). For Lake Tana, the stability will depend on the test using the meteorological data of wind speed. Given its size of 3156 sq km, the build up of turbulence (wind eddies) because of the water as a source of moisture that increases momentum flux is evident. This could be observed from two adjoining sites of the lake one a major town called Bahir Dar with wind breaks and the other a flood plain with no wind shelter. The momentum of the wind dies abruptly in both cases as it goes out of the lake indicating that the momentum flux is dependent on the moisture source than presence of the wind breaks. This suggests that evaporation estimation from the lake should differ in approach from the land surface and mass transfer would be relevant for the lake though it could be certain period of the season or day.

Pan Method is also often used to estimate evaporation from free water surface. Nevertheless its relevance is skewed to small ponds for the size, sensitivity to perturbation of temperature and reasonable accuracy of specific heat capacity of ponds (Lee, 2000).

Runoff

Water balance estimates are highly sensitive to runoff (CEEPA, 2000) and for any sensitivity analysis of the water balance against precipitation, an established relationship of runoff with precipitation in any distributed model could be important. However, in areas where paucity of data is evident little can be done in the lumped water balance modeling. Inflow to the lake from the four major rivers is taken as input to the water balance.

Ground water

In most ground water modeling exercises, models such as MODFLOW (Anderson and Woessner, 1992), and MIKESHE (Hai et al., 2007) are proven helpful. But equally, numerical methods namely iterative finite difference methods have shown simplicity without compromising accuracy of results.

A numerical method for groundwater flow representation using a Poison’s equation (Wang and Anderson, 1982) is indicated as follows.

For steady state $$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{E}{T} \tag{3}$$

For transient flows

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{T}\frac{\partial h}{\partial t}+\frac{E}{T} \tag{4}$$

Where h = head; T = transmissivity; E = evapotranspiration, S = storativity, t = time

The choice is dependent on the level of complications. In either of the cases, use of hydrogeologic units and well representation of the boundary and initial conditions would be vital to simplify the modeling process. For complex physical models, use of the MODFLOW is encouraging while the numerical methods could be sufficient to address in flat plains with sound boundary and initial conditions. Understanding ground water flow patterns at different seasons and geological structures help to determine the physical hydrogeologic units. Leakance to an aquifer and evapotranspiration from the land surface is major inputs for the modeling exercise. Measureable variables namely, hydraulic conductivity would be obtained from secondary sources (Kebede et al., 2005) though expert judgment could still help to use it in context. Lastly availability of hydraulic head ‘h’ is vital for calibration of the models.

METHODOLOGY

The physical level water budgeting is done based on conservation of mass summing up components of inflows and outflows in the system. The components (identified in the water cycle) include precipitation (P), evapotranspiration (ET), river inflow/outflow, ground water recharge/discharge (G) and change in surface storage (ΔS). P +

$$\text{River Inflow}+G_{inflow}-\text{ET}-\text{River outlow}-G_{out}\pm\Delta S= 0 \qquad (5)$$

Precipitation was acquired form the rain gage information monitored by the Ethiopian Metrological Agency. Discharge data on river were acquired form the Ethiopian Ministry of Water Resources. ET was estimated based on data from satellite information acquired from U.S Geological Survey (USGS) and also metrological information from the Ethiopian Metrological Agency.

Data Analysis

Precipitation

Point measurements of precipitation are collected from secondary sources and developed to ArcGIS (ESRI, 2007) format point shape files from which Kriging was employed to interpolate and extrapolate the precipitation distribution over the lake. The farthest precipitation measurement is Debre Tabor, about 45 km from the periphery of the lake. Kriging is employed to cover the geographical variation of the rainfall. It observed that the rainfall over the lake is dominated by the northern part of the lake (Gondar). The analysis showed that contribution of the rainfall to the lake amounts to 3.78 billion cubic meter (BCM) contributing, which is 50% of the total inflow.

Lake Evaporation

The daily lake evaporation estimation is carried out using three methods: energy balance (Penman Method), mass transfer (Meyer's deterministic formula) and a simplified approach (Thornwaite Method). It is found out that the energy budget equation may not be stable for April, May, June and July as the Bowen ration is showing negative values. Similarly, the stability parameter SMT has shown small values in

September, October, November and January suggesting a comparative advantage of the two approaches in different seasons.

Penman Equation

The energy balance approach is represented by Penman Method using the equation below as

$$E_{tp} = \frac{\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma}6.43(1+0.53u_2)(e_s - e_d)}{\lambda} \qquad (6)$$

E_{tp} = Potential evapotranspiration in mm/day, R_n = net radiation in MJ $m^{-2}d^{-1}$, G = heat flux density to the ground in MJ $m^{-2}d^{-1}$, λ = latent heat of vaporization in MJ /kg, u_2 = wind speed measured 2m above the ground in m/s, Δ = Slope of the saturation vapor pressure – temperature curve, KPa/^{o}C, γ = psychometric constant, KPa/^{o}C, e_s-e_d = vapor pressure deficit in kPa. The detailed parameters computation is shown in (Ward and Elliot, 1995)

For Penman estimation, mean monthly temperature and elevation data are collected from Ethiopian Metrological Agency while wind speed and solar insolation for Bahir Dar station are collected from World Metrological Organization.

Table 1. Meteorological data, (WMO, 2008)

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Insolation, kWh/m²/day	5.8	6.2	6.5	6.6	6.3	5.7	5	5	5.7	5.9	6	5.7
Clearness, 0 - 1	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.6	0.7	0.7
Temperature, °C	21.1	22.4	23.5	22.5	21.4	19	17.9	17.9	18.8	20.3	20.6	20.6
Wind speed, m/s	4.1	4.3	4.1	4.1	4.1	5.1	5	4.2	3.5	3.1	3.8	4.1
Precipitation, mm	4	3	9	24	84	178	438	386	199	90	22	4
Wet days, d	2.2	2.7	3.6	5.4	8.2	11.5	12.4	14.4	10.7	5.5	2.4	1.8

Mass Transfer Approach

Meyer's approach is based on the deterministic approach derived from the general boundary layer atmospheric system. The underline assumption as stated elsewhere is that the turbulent production term overweighs the buoyancy on open water surfaces of large sizes such as lake, and big dams. Results are location independent for estimation of evapotranspiration. It is computed using the following formula (Lee et al., 2000).

$$E = C\,(e_s - e_d)\,(1 + u_{25}/10) \quad (7)$$

E = Evaporation (in/month), e_s = Saturation vapor pressure (in of Hg) of air at the water temperature 1ft deep, e_d = actual vapor pressure (inches of Hg) = $e_{s(\text{air T})}$ * RH,
u_{25} = average wind velocity (mi / hr) at a height of 25 feet above the lake or surrounding land areas, C = Coefficient; 11 for small lakes and reservoirs and 15 for shallow ponds

Meyer's approach demands determination of surface temperature of the lake unlike the Penman method of air temperature for the energy budgets. For this purpose, two years lake surface temperature is estimated using 24 satellite images from 1999 & 2005 (two images for each month). The images are radiometrically corrected by converting the digital number value in Landsat thermal band (band 6-1 and band 6-2) to radiance values. Afterwards the radiance values were changed to effective temperature value according to Landsat-7 ETM handbook of NASA as validated in different studies (Bambang et al., 2001). The conversions are found as follows.

$$L_\lambda = ((LMAX_\lambda - LMIN_\lambda)/ (DNMAX-DNMIN))*(DN-DNMIN)+LMIN_\lambda \quad (8)$$

$$T_{Landsat} = K_2/ \ln((K_1/ L_\lambda)+1) - 273 \quad (9)$$

Where L_λ ; Spectral radiance watts/(m*m * ster * µm), DN ; Digital Number, $LMIN_\lambda$; Spectral radiance which is correlate with DNMIN watts/(m*m * ster * µm), $LMAX_\lambda$; Spectral radiance which is correlate with DNMAX watts/(m*m * ster * µm), DNMIN; Minimum value of

DN (1 (LPGS Product) or 0 (NLAPS Product)), DNMAX ; Maximum value of DN = 255, $T_{Landsat}$; Effective temperature (Celsius), K_1; 666.09 W/(m*m*ster*µm), calibration const, K_2; 1282.71 W/(m*m*ster*µm), calibration const, Value of $LMIN_\lambda$, $LMAX_\lambda$, DNMIN and DNMAX are in the header file information (meta data) that comes with the Landsat data.

Mean monthly air temperature is also derived from temperature anomaly simulation by the GHCN_NOAA. The scatter confirms that the GHCN temperature has 1:1 relationship with the meteorological data while mean lake surface temperature is 3°C above the air temperature confirming an accepted relationship (Kebede et al., 2005). The scatter diagram shows an overestimation by the satellite-based temperature estimation. This could be associated with the dominance of shallow depth of the water in most parts of the lake inflating the radiance value.

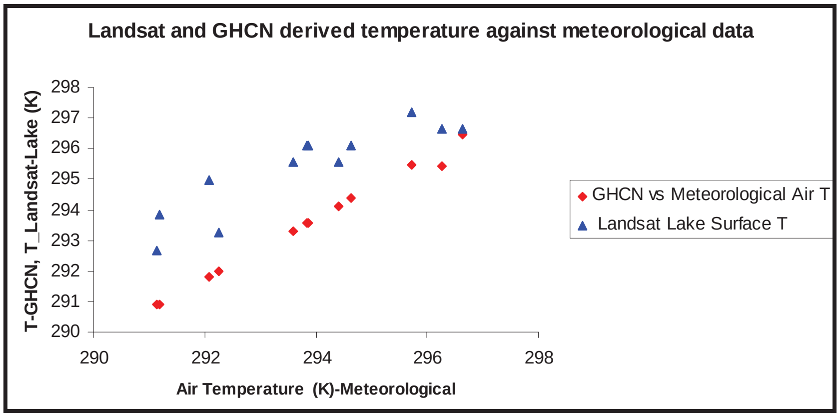

Figure 2. Lake Tana surface Temperature (°K) determined based on Landsat ETM+ correlated with GHCN and meteorological air temperature.

Temperature perturbation (anomaly) data (1972-2005) is derived from the GHCN_NOAA and compared to the mean monthly temperature of the meteorological data for the years of analysis (Figure 2).

Thornwaite Method

The Thornwaite Method is suggested for its temperature data dependence only.

$$Etp = 16\ [10T/I]^4 \qquad (10)$$

Where Etp = Monthly ET in mm, T = Mean monthly temperature in ^{o}C, a = location dependent coefficient described by

$$a = 6.75X10^{-7}I^{3}-7.71X10^{-5}I^{2}+1.792X10^{-2}I+0.49239 \qquad (11)$$

where I = $\sum_{j=1}^{j=12}\left[\frac{T_j}{5}\right]^{1.514}$

Tj is the mean monthly temperature during month j (oC)

Comparison of the three evapotranspiration estimation methods is shown in Figure 3. The energy budget and mass transfer have shown their seasonal advantages. From January to June, when the buoyancy dominates the turbulent production, Penman’s method could be relevant. The turbulent production has dominated from June to October, suggesting the relevancy of the Meyer’s Method. In all the cases, the Thornwaite Method has underestimated the evapotranspiration from the lake. For estimation of the monthly water budget, both the energy and mass transfer methods are used. The annual water budget is estimated using the Thornwaite method for reasonably low propagated errors from derivation of the historical temperature data whose perturbation is limited to -1.5 ^{o}C up to 1.5^{o}C.

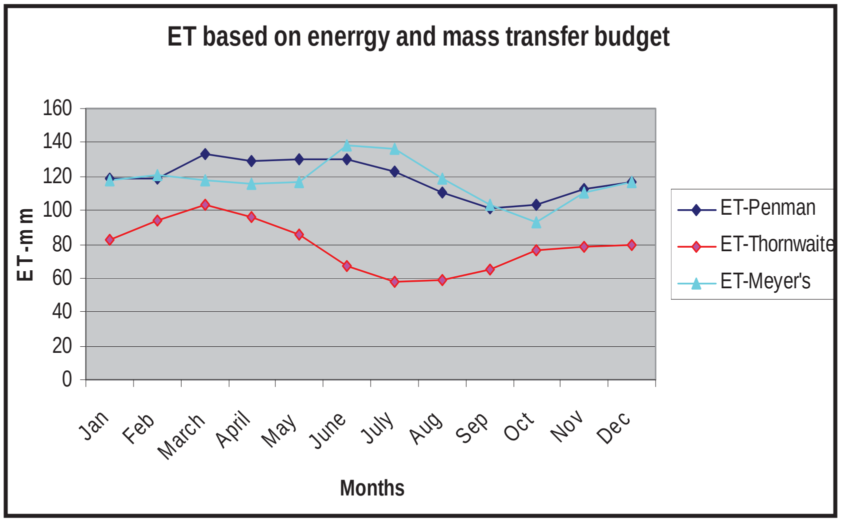

Figure 3. Monthly ET estimated for Lake Tana using the three methods.

Groundwater Flow

Preliminary analysis is first done to estimate the ground water inflow into the lake. Whereas the outflow is less significant given the less permeable basalt that dams the lake (Kebede et al., 2005). In order to understand the groundwater dynamics, one of the sub-basins namely Gumera was used to look at the flow in the sub-basin. This hydrogeological simulation through forced boundary condition has shown that in both the dry and wet season, the hydraulic head is concentrated near the streams showing that the flow is a subdued form of the watershed relief flowing across the outlet, not differing from thin section across the stream courses. This gave a clue that the ground water input from the watershed would be captured from the base flow of the stream and the flow through the thin unconfined section. A separate contribution is identified from the flood plain that is flooded for months during the rainy season and starts to yield into the lake during the dry seasons. This contribution is from a 20 km section of flood plain which carves as a concentric circle centering Lake Tana (Figure 4).

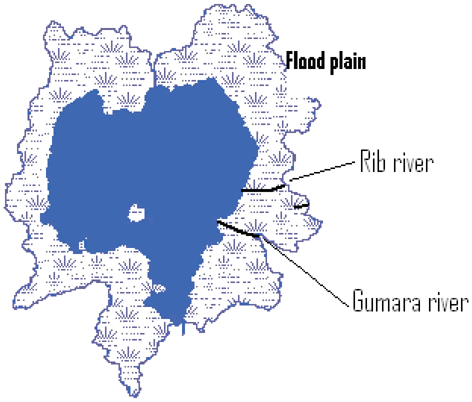

Figure 4. Lake Tana flood plain.

The hydraulic head distribution from the simulation for the dry season indicate that subsurface flow is from the rivers towards the flood plains, higher heads near the rivers with decreasing gradient towards the main land. The hydraulic head is calibrated against shallow wells in the flood plain and it is found out that the flood plain receives about 0.16 billion cubic meters (BCM) from base flow of the rivers, while the flood plain itself contributes 0.1BCM to Lake Tana. The difference (6 millions m^3) is being stored in the flood plain. A one dimensional transient flow simulation for the wet season indicates the reversal of the head distribution.

Runoff

River flow data gauged by Ethiopian Ministry of Water Resources in all the sub-basins including the outflow of Blue Nile at Bahir Dar is used in this analysis. Inflowing rivers identified are Rib, Megech, Gumera, and Gilgel Abay. The outflow is the Blue Nile river discharge just at the outlet of Lake Tana. Mean annual, mean monthly and monthly flows of 42 years data (1960 to 2003) is used to analyze the flow (Figure 5). The relationship indicates the outflow has an extended recession limb seemingly tipping the storage. The surface water inflow from the four sub-basins is about 3.5BCM making up 42% of the total inflow while the outflow at the outlet of the Blue Nile amounts to 5.3BCM.

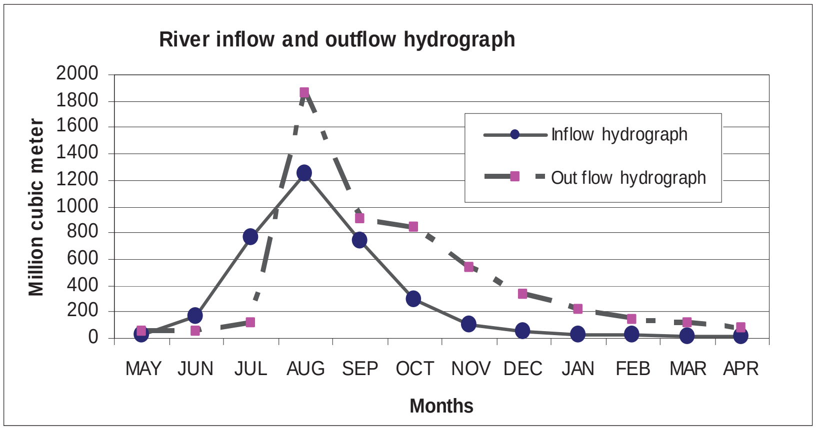

Figure 5. Inflow and outflow hydrograph of Lake Tana.

The monthly computed balance against the measured lake level shows a reasonable fit with RMSE value of 0.17m (Figure 6). The calculated lake level using different approaches of ET estimation is plotted against the measured values and it suggests no significant difference because of the distribution over months. However, on annual basis, the mass transfer method accounts to additional loss of 85mm (0.25BCM). Component wise precipitation contributes about 54% (4.26 BCM) and sub-basin level subsurface water inflow contributes about 3% (0.27BCM, dry and wet season combined). The total outflow at the outlet amounts to 5.3BCM while evapotranspiration attributes 45% of the loss (4.6 BCM). Looking at the overall balance, the inflow shows a deficit of 10% against the outflow suggesting the contributions of unaccounted inflows. The unaccounted inflows are runoff from the flood plain, regional groundwater flow, and some incurred error. In previous studies, assumptions are often held attributing 7% groundwater contribution to the inflow (Kebede et al., 2005). This is confirmed reasonable, though it should include the runoff from the flood plain.

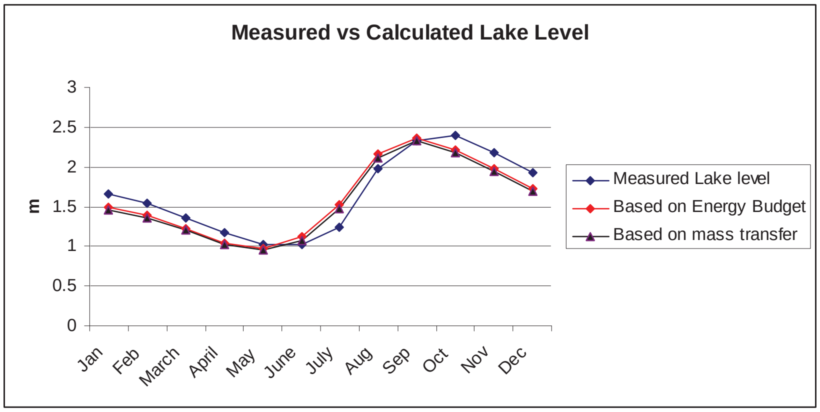

Figure 6. Measured vs. calculated average monthly Lake Tana Level using ET estimation based on energy budget and mass transfer.

The annual water budget is based on Thornwaite Method (to reduce propagated error). Historical temperature data for considerable number of years is derived from GHCN which shows a 1:1 relationship with mean monthly temperature data (Figure 2). As it is observed on Figure 7, all the computed values have underestimated the evapotranspiration. On annual basis it underestimates loss of 1.5BCM. Even then differences on annul measured and calculated lake level indicate a goodness of fit with RMS value: 0.15

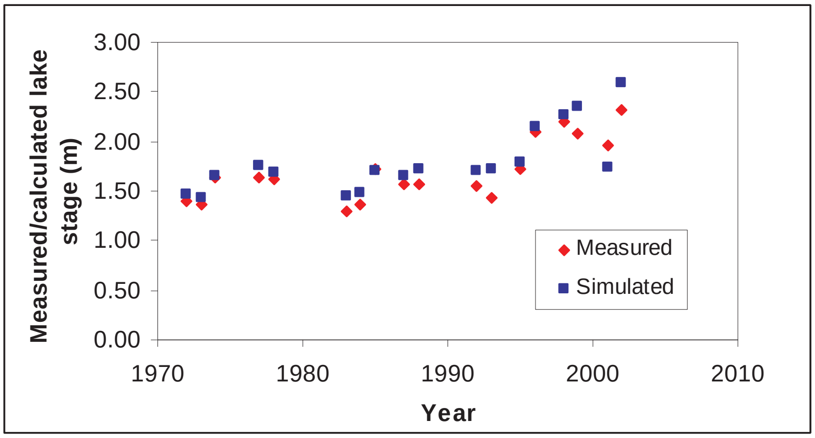

Figure 7. Mean annual stage levels of Lake Tana (1960-2003). Lake stage is referenced at 1783.5 m amsl.

CONCLUSION

At the outset the objective of this study was set to review water balance parameters and undertake lumped modeling over Lake Tana. The review is met with deeper understanding of precipitation distribution, evapotranpiration governing factors, groundwater flow patterns and runoff contribution. For Lake Tana scale point measurement of rainfall and application of kriging looks viable. However, it was discovered that except around the peripheries of the lake most of the sub-basins that have hilly topography are ungauged demanding other techniques (e.g. Satellite imagery) of precipitation measurement. Runoff measurement is also at station level and a distributed estimation has suffers from lack of temporally distributed precipitation data and spatially disaggregated measurement or estimation.

Though the result on the overall balance was not significant, it is learnt that the energy budget and mass transfer methods of ET estimation disparate seasonally in high turbulence production vs buoyancy dominating seasons. This suggests seasonal applications of the two methods especially for open water surfaces of ponds, dams and lakes. In this study, the seasonal application the two methods is seen to give better estimate than the sole use of any of the methods. With more accurate estimation of the unguaged runoff from the flood plain the balance using the combined methods of the evapotranspiration would give the best fit.

Further studies to validate the work with more data on groundwater flow, unaccounted runoff ad small streams contributions and precipitation data with good distributions of rain gages will help strengthen the results shown in this study.

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