Hydrology of the Lake Tana Basin, Ethiopia: Implication to Groundwater-Surface Waters Interaction

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Abstract
Hydrological studies have been done in the Lake Tana basin to determine the groundwater recharge rate based on different methods, groundwater inflow to and outflow from the Tana Lake, and to understand the groundwater and surface waters interaction. Recharge rates of 195.6, 284.0 and 285.4 mm/year have been estimated based on base flow analysis, chloride mass balance (CMB) and soil water balance (SWB) methods, respectively. Base flow separation method shows mean shallow aquifer recharge that feeds the streams. The recharge estimates from CMB and SWB are nearly similar and the average of the two (284.7 mm/year) can be taken as the mean basin recharge rate. The difference between the basin recharge and the base flow (89.1 mm/year or 31.3% of the recharge) contributes to deep aquifers recharge.Tana Lake balance study has also showed leakage underflow of 954.8 hm^3/year, which mixes with groundwater mainly in the Beles basin and to some extent in Tis Abay area. Groundwater inflow directly to the lake is found to be negligible.
Keywords: groundwater recharge, water balance, base flow, groundwater and surface waters interaction, Lake Tana, Blue Nile River, Ethiopia

1. Introduction

Water use competition is seen in Tana basin among hydroelectric, irrigation, tourism, water supply, navigation and environmental needs such as river base flow and wet lands, and this will be a serious issue in the future. Groundwater is a sole source of water supply for towns, industries and rural communities. Currently, there is an attempt by the Federal Government to develop groundwater using deep boreholes and rivers using dams for medium and large scale irrigation in the area.

However, many wells drilled have poor productivity and some have poor quality. Drying of wells and springs has also been reported after prolonged drought. This shows that the effective use of groundwater has been hampered due to complex nature of aquifers and partly because the hydrogeological system and sustainable yield of the aquifers and the basin were not adequately explored, which led to difficulties in locating productive aquifers and sustainably develop the groundwater.

Besides, the intended groundwater development for irrigation will overdraft the groundwater reserve and entails drying of streams' flow that will have adverse effect on the current irrigation schemes using rivers, on riparian ecology, and on existing and future groundwater water supply schemes.

Estimation of reliable and proper recharge rate helps to determine the basin and aquifer safe yield. Besides, understanding how the groundwater interacts with the streams and Tana Lake will have implication and positive impact on the long term integrated planning and sustainable development of the water resources in the basin.

Water supply investigations of specific towns and studies and researches that cover part of the Tana sub-basins and a few that cover the whole Tana basin as well as regional ones that consist of the basin have been done to solve the problem. These hydrological and hydrogeological works attempted recharge evaluation and groundwater and surface water interactions.

The recharge estimates of previous authors mainly use different hydrograph separation method, and are variable and often under estimated. Recharge rate may be calculated by different methods. Because of the uncertainties associated with each method, the use of many different approaches is recommended to constrain the recharge estimate (Scanlon, et al., 2002). In humid areas like the Tana basin, base flow separation and soil water balance methods are appropriate (Scanlon, et al., 2002).

Therefore, the chloride mass balance that accounts surface runoff, soil water balance and hydrograph separation methods were used here to estimate reliable basin recharge rate under this study. The recharge estimated by the different methods helped to understand the streams-groundwater interaction.

All previous except the works of WWDSE (2007) concluded the Lake Tana basin as closed system in terms of groundwater inflow and outflow, and groundwater inflow to and outflow from the lake were considered negligible. WWDSE (2007) speculated possible lake water underflow to the northern adjacent basin, no outflow to Beles basin, and significant lake water outflow to the deep aquifer in the eastern area via the lake floor.

Thus, this controversial issue has to be resolved and interaction of the Lake Tana with the shallow and deep aquifers, as well as rivers and groundwater interaction have to be determined by this study. All previous lake water balance studies did not consider the groundwater inflow to and outflow from the lake. The hydrological and chemical mass balances of the Tana Lake have been evaluated here, which considered the groundwater inflow and outflow, as well as the un-gauged catchment runoff.

Further details about the different methodologies employed are given in Section 3.

The present recharge and Tana Lake balance studies has resolved these problems and give new insight to the water resource management of the area. The specific objectives of the study include:

- Basin groundwater recharge evaluation based on base flow separation, soil water balance and chloride mass balance methods
- Estimate groundwater inflow to and outflow or leakage rate from the Tana Lake
- Decipher groundwater and surface waters (rivers and Tana Lake) interactions

2. Description of the Area

Tana basin is the head of the Abay or the Blue Nile River. It is located within UTM zone 37, between 252788 and 396487 mE longitude, and 1218577 and 1410176 mN latitude (Fig. 1). The basin has an area of 14879.4 km^2, of which Tana Lake occupies 3057.4 km^2.

Rugged mountainous volcanic terrain, moderate to gentle terrain in volcanic rocks with some isolated hills, escarpment and plain constitute the physiographic units of the area.

Tana basin is characterized by 0.04, 0.3, 15.2, 28.9, 53.3 and 2.2 % of Afro-Alpine, Sub-Afro-Alpine, Temperate (Afro-Mountain), Subtropical (Wooded- Savannah), Subtropical (Shrub- Savannah) and Subtropical (Savannah) climatic zones, respectively. The area is characterized by uni-modal type of rainy period, which is from May to October. The aerial average precipitation and potential evapotranspiration of the Tana basin are 1400.4 and 1329 mm/year, respectively.

The mean annual air temperature varies between the lowest 15.8 °C at Debre Tabor meteorological station, and the highest 20.6 °C at Gonder station.

Rivers that flow into eleven sub-basins drain the area (Fig. 2). Most of the rivers in these sub-basins are perennial. These rivers flow into the Tana Lake.

Lower Basalt/Ashangi Basalt (Eocene), Middle/Aiba and Upper/Alaji basalts (Oligocene) form the Tertiary Trap series in the area. The Lower/Ashangi Basalt was found in boreholes underlying the Middle/Aiba Basalt. Degoma Basalt, Sekela Basalt, Guna Tuff, Guna Basalt, Guna Phonolite, trachytic plugs and flows are also found in the area, which are the results of Miocene-Pliocene shield volcanoes. Quaternary basalt and rhyolite dome, and Quaternary fluvio-lacustrine sediments also occupy the moderate slope and plain areas (Fig.3).

Normal faults and lineaments of dominantly NNE-SSW, WNW-ESE, and multi sets of macroscopic joints that are open and interconnected cut the volcanic rocks.

Lithological units have been grouped in to three categories: inter-granular and fracture aquifers, and aquitard (Fig.3).

The fluvio-lacustrine sediments and Guna tuff are considered as intergranular aquifers in which groundwater flow is via porous media. The Tertiary and Quaternary volcanic aquifers are fracture aquifers where flow is mainly through fracture networks and weathered mantle. The rhyolite domes and trachytic plugs are assumed to be aquitard because of less primary water bearing characteristics and fracturing.

The fluvio-lacustrine sediment aquifer consists of clay at the top and sandy beds at varying depths especially toward the pediments. Bedded tuff and loose friable mud inter beds also seen in this deposit. Borehole depth in this aquifer varies from 45 to 118 m. Available few pumping test data showed that transsmissivity varies between 2.1 and 34.8 with a mean and median of 16.9 and 13.7 m^2/d, respectively. This aquifer is assumed to have low to moderate productivity.

The Guna tuff aquifer is loose to weakly compact with welded tuff inter beds. A borehole drilled in this aquifer with a depth of 42 m has transsmissivity of 13.7 m^2/d. This suggests that the aquifer has low productivity.

Middle and Upper basalts aquifers are fractured and weathered, with some pyroclastic deposits and ignimbrite layers for the latter. Individually, these aquifers have average transsmissivity that indicates low productivity. However, the productivity varies spatially and with depth depending on the degree and interconnectivity of fractures and presence of scoria beds. Transsmissivity in these aquifers varies from 1.1 to 157 m^2/d. Better productivity or transsmissivity and borehole yield have often been obtained in deep boreholes (>300 m) that intersected the Upper and Middle basalts, and the underlying Lower basalt aquifers. Transsmissivity as high as 72 m^2/d were attained in these boreholes.

Degoma Basalt, Guna Basalt and Guna Phonolite often occupy steep and rugged terrains and generally are considered to have low productivity. They are not generally suitable for boreholes, but for dug wells at the plateau tops and low yield spring development at slopes.

Trachyte flows have very low thickness (less than 25 m) and form often the unsaturated zone.

Sekela basalt is weathered, fractured and scoraceous. Dry period spring yield of 10 to 30 l/s has been seen in this aquifer and it seems to have moderate to high productivity.

The Quaternary basalt aquifer is highly fractured, vesicular and scoraceous. It is underlain by the Tertiary basalts. Boreholes drilled in the Quaternary and underlying Tertiary basalts aquifers have depths of 23 to 198 m. Transsmissivity often varies between 6.3 and 677 with a mean and median of 118 and 43.7 m^2/d. Springs emanating from this aquifer have discharge of as high as 150 l/s. This aquifer has generally high productivity.

Shallow unconfined and deep (semi) confined aquifers are anticipated in the area based on hydrogeological, hydrogeochemical and isotopic tracers investigations as part of this research.

Groundwater generally flows from the surrounding mountain towards the Tana Lake (Fig. 3). Deep confined paleo groundwater has been deciphered below the shallow groundwater in the eastern part of the area, which emerges at the oozing salty spring through lineament.

Recharge takes place from precipitation in volcanic terrains and little recharge may take place in fluvio-lacustrine sediments aquifer at the plain. Recharge at the eastern and northern part of this aquifer may also occur from influent streams and seasonal flood pools, and back lake water inundation. Furthermore, groundwater recharge occurs from reservoirs made in the volcanic terrains.

Basin water balance, hydrogeochemical and isotopic (oxygen-18, deuterium and tritium) data from this study showed that there is considerable basin groundwater outflow from Tana basin to the adjacent low lying Tis Abay area (Fig.3).

Evapotranspiration from the shallow groundwater at the margins of the Tana Lake and abstractions are other mechanisms of the groundwater discharge.

3. Approaches and Methodology

3.1 Data Processing

Hydrological, hydrogeological, hydrogeochemical and environmental isotopes investigations have been done to understand the system, how it functions and to understand the groundwater and surface waters interactions.

Monthly meteorological data have been collected for a total of 12 stations for the period between 1995 and 2009 from the Ethiopian National Meteorological Agency, which are used to calculate aerial average precipitation and reference potential evapotranspiration values for the whole basin and average precipitation over the Tana Lake.

The point monthly precipitation data of Bahir Dar, Dangila, Addis Zemen, Debre Tabor, Gonder, Gorgora, Zege and Sekela stations have been averaged and were weighted using Thiessen polygonal method to get distributed aerial rain fall (P) of the basin using ArcGIS 9.3. Similarly, rain fall over the Tana Lake area (P_l) has been aerially averaged using Thiessen polygonal method using the nearby Wereta, Gorgora, Delgi, Kunzila, Dek Estifanos, Bahir Dar and Zege stations in annual basis.

The mean monthly (1995-2009) reference potential evapotranspiration (ET_o) has been estimated for Bahir Dar, Dangila, Addis Zemene, Gonder, Gorgora and Debre Tabor stations using Penman-Monteith method with the help of the FAO (2009) software known as Cropwat version 8.0.

Most parts of the study areas have subtropical and temperate climates while others have sub-afro-alpine and afro-alpine type of climates. Therefore, this method gives reasonable reference evapotranspiration data for the area.

The aerial average monthly reference potential evapotraspiration has then been estimated with the help of Thiessen polygonal method.

Actual evapotranspiration (AET) has been calculated during soil water balance computation by simple book keeping method.

Open water evaporation (E_{ol}) from the Lake Tana has been estimated using Penman's method. Penman's equation is based on theoretical reasoning, which is a combination of the energy balance and mass transfer approach, and calculation was done as used by Surbamanya (2004) and Shaw (1994).

Estimation of the Tana Lake evaporation based on the Penman's method has been done using Bahir Dar meteorological station data, which is close to the lake.

Open evaporation has also been calculated from mean monthly (1995-2009) Pitche evaporation data of Bahir Dar station. A conversion factor of 0.75 (Tenalem 1998) has been used to estimate the lake evaporation. Then, average value of the evaporation rates obtained by Penman's equation and from Pitche evaporation data have been estimated and used for the Tana Lake balance evaluation.

Open water evaporation (E_{opm}) has been considered on the permanent marsh, which is found at the margin of the lake, and the magnitude is considered to be equal to the lake evaporation rate. On the other hand, seasonal marshes or flood pools that develop during the wet period (August to November) are assumed to have open water evaporation, which is similar to the lake evaporation rate, for this period. During the rest dry period, it is dry and will have the actual evapotranspiration values estimated for the given months (E_{osm}). These data are given in Table 1.

Lake Tana basin is drained by a number of perennial and seasonal streams and rivers, which form eleven sub-basins. All streams and rivers flow into the lake. Surface outflow from the lake is only through the Abay or Blue Nile River.

River inflow to the lake has been gauged at 10 stations of different rivers (Fig. 2). Daily rivers' discharge data (1995-2009) have been collected from the Ministry of Water, Irrigation and Energy and used to analyze the groundwater base flow.

Surface water or river inflow to the Tana Lake from gauged catchments has been estimated using the eight hydrological stations in annual basis, excepting Amen, and Gelda stations, which have small catchment areas and the latter unexpectedly with high runoff (Table 2).

However, there is also surface water inflow to the lake from un-gauged catchments. The un-gauged surface runoff has been estimated using runoff coefficient of 0.314 multiplied by the annual aerial average precipitation (1400.4 mm/year) and the total un-gauged catchment area of 5134.1 km^2 (Table 2).

The mean monthly surface water outflow of Lake Tana basin by the Abay or Blue Nile River is also given in Table 2.

Then, the results obtained from the above procedures have been plugged into the different recharge estimations (hydrograph separation, soil water balance and chloride mass balance methods), and Tana Lake balance evaluations. These methods are further described as follows.

3.2 Recharge Estimation Methods

3.2.1 Base Flow Separation Method

River hydrograph consists of surface runoff, interflow, and groundwater base flow and channel precipitation. Interflow and the contribution from the precipitation are usually taken lumped to surface runoff during hydrograph separation and termed as direct runoff (DRO). Base flow separation has been done using 15 years (1995-2009) daily streams flow data at 8 hydrological stations that are situated at different parts of the basin. Because, base flow separation method is applied here over long period of hydrological records, the effect of change in storage can be considered negligible.

Base flow indices (BFI), which is groundwater base flow divided by the total river runoff, have been estimated for each station and period used. In case where there is year with missing data of more than 3 months, it is omitted and BFI have been estimated separately for the different consecutive periods for a given station. Weighted mean BFI by the number of years used is then calculated for the station (Table 3).

River Analysis Package software (RAP) developed by Monash University Melbourne (Australia) and Lyn-Hollick (1979) digital filter algorithm have been used to estimate the BFI.

The Lyn-Holick digital filter has one parameter, which is the α value. Grayson et al (1996) recommended a value of 0.975 for α (Marsh et al. 2003). This filter parameter value has been found appropriate and adapted in this analysis, and gave reasonable hydrograph separation.

3.2.2 Soil Water Balance Method

Soil water balance method uses the surplus water as a recharge. This method is widely used for regional recharge estimation. Spatial changes in evapotranspiration due to changes in soil and vegetation types can be incorporated in this model and the model has a simple scheme to distribute surplus water into successive months (Tenalem 1998).

Soil and land cover maps of the Tana basin have been prepared. These maps have been overlaid using Arc GIS 9.3, and the aerially weighted available water capacity of the area have been estimated to be 165 mm using the available water capacity (% volume) of soils and rooting depth (meter) of vegetations as used by Thornthwaite and Mather (1957).

Aerially averaged monthly precipitation (P) and reference evapotranspiration (ET_o), based on Thiessen polygonal method, have been used in the soil water balance computation (Table 1).

Different types of crops (dominantly maize, sorghum, wheat, teff and rice in decreasing order) and natural vegetations (often grass, short bushes and shrubs) grow in the area, and it is difficult to ascribe crop coefficient (K_c) values for each crop and vegetation as their area coverage is unknown. About 87% of the total study areas are agricultural land, and the farmers exercise crop management practices.

The rain fall is frequent to wet the soil and the crops are often kept to dry in the field during the late growing season. Average value of the average crop coefficients during the initial, mid and late growing periods (Allen et al. 1998), which is equal to 0.88, has been calculated and used for all months to calculate crop evapotranspiration (ET_c) from the reference evapotranspiration, and then soil water balance computation was done.

Weighted (by area), direct runoff (DRO) has been derived from partitioning of the river hydrograph using the River Analysis Package software (Section 4.2.1) in annual basis. Then, the runoff coefficient has been calculated as quotient of DRO to the mean annual precipitation. The monthly direct runoff has been derived by multiplying the mean monthly precipitation by this runoff coefficient value.

Evaluation of the soil water balance has been done by simple book keeping method. The recharge is estimated as a residue of precipitation minus direct surface runoff, ET_c and the positive soil accretion (Table 4).

3.2.3 Chloride Mass Balance Method

The chloride mass balance (CMB) approach may be used both in unsaturated and saturated zones to estimate recharge. It is based on the assumption of conservation of mass between the input of atmospheric Cl and the Cl flux in the subsurface.

CMB method for saturated zone may be especially useful in areas where groundwater levels do not fluctuate or data on groundwater levels are lacking. CMB is often applied in semi arid and arid regions where the impact of runoff should not have been taken into account and evaporation effect on the recharge water is significant. However, it is frequently used also in other areas. According to Cook (2003), despite the short comings, the CMB method is highly recommended even for fractured rock system (Beekman and Xu 2003).

Basin groundwater recharge can be estimated as follows **(**after, Eriksson and Khunakasem 1969; Wilson and Guan 2004**)**

$$R = \frac{C_pP - C_qQ + D}{C_{gw}} \quad \ldots\ldots (1)$$

Where, C_{gw} is Cl in groundwater, P is precipitation over the basin, C_p is Cl in bulk precipitation, Q and C_q are runoff and its Cl content, D is dry Cl deposition, R is recharge

In industrial areas, gases and aerosols that may contain substantial Cl may pollute the atmosphere and lead to high levels of dry deposition (Nyagwambo 2002). Dry deposition must be considered in areas within or downwind of atmospheric pollution source. The amount of deposition is a function of the atmospheric concentration of gases, aerosols and the velocity at which they are deposited.

The bulk Cl deposition, which is measured in rain gauge monthly during wet season incorporate the dry deposition of the preceding month. Thus, the bulk deposition nearly represents the total (dry + wet) atmospheric Cl deposition, and the wet season Cl concentration measured at the rain gauge can be taken in the calculation (Nyagwambo 2002).

There are no much industries in the area. Furthermore, the rain gauges, where the rain fall samples have been collected, have low height than the natural vegetations and most of the crops growing in the area. Hence, dry fallout from intercepted water by vegetation and crops if any can be captured by the rain gauge.

Aerial average basin precipitation, which is calculated using 15 consecutive years' data have been used in CMB computation. Rain fall sampling was conducted for one hydrological year in four meteorological stations distributed within the basin. After the weighted (by precipitation) mean content of Cl in each station is calculated, harmonic mean of the Cl content for the four stations has been estimated and used in the recharge estimation.

Mean weighted annual surface runoff, which is obtained by hydrograph separation method (Section 4.2.1, Table 3), was used here. Cl concentration of rivers at different streams was measured and a harmonic mean of these data has been considered for CMB evaluation.

Harmonic mean of Cl concentration of groundwater (boreholes, springs and dug wells) samples was taken in this computation. Groundwater points with anomalously high Cl values, which are concluded to be due to local dissolution of trace halite and sylvite in the lacustrine sediments, and those of old ground waters have been omitted.

3.3 Lake Balance Method

The hydrologic balance of the lake is based on the mass conservation law or hydrological continuity equation. Lakes' water budget is computed by measuring or estimating all of lake's water gains or losses, and the corresponding change in lake volume over the same time period and has the form as given below (Rozanski et al. 2001; Sacks et al. 1998):

$$dV_L/dt = S_i + G_i + P_l - S_o - G_o - E_{ol} \quad \ldots\ldots (2)$$

Where, V_L is lake volume. S_i, G_i, S_o and G_o represent the volumetric surface and groundwater inflows, and outflow fluxes, respectively. P_l stands for precipitation over the lake and E_{ol} is the evaporation flux from the lake. S_i includes both gauged and un-gauged surface water inflows. dt represents time period over which estimation is done.

The chemical mass balance approach uses naturally occurring conservative tracer (e.g. Cl) and combines the water budget equation with solute balance equation. This approach also applies mass conservation law to the tracer constituents, which are dissolved in water. The Cl tracer can be assumed as conservative that is not significantly involved in any geochemical or biological reactions, which alter its concentration (Sacks et al. 1998), and it is often used in lake balance evaluation. The mass balance equation written for chemical tracer (Cl) has the following form:

$$C_L \times dV_L/dt + V_L \times dC_L/dt = C_{Si} \times S_i + C_{Gi} \times G_i + C_{Pl} \times P_l - C_{So} \times S_o - C_{Go} \times G_o - C_{Eol} \times E_{ol} \quad \ldots\ldots (3)$$

Where, C with the respective subscripts represents the concentration of the tracer (Cl) in the lake and in all incoming and outgoing water fluxes.

Long term mean annual values (1995-2009) of P_l, S_i, S_o and E_{ol} have been used. Furthermore, average Cl value of groundwater inflow (from boreholes, springs and dug wells), river inflows, and average Cl content of precipitation sampled at Gonder and Bahir Dar meteorological stations that are close to the Lake Tana, after weighted (by precipitation), and that of the Tana Lake have been used in this lake balance evaluation.

The lake is shallow with average depth of 9m (Seifu et al. 2006) and considered to be vertically mixed. A steady state lake with respect to the bulk mass of water and the Cl tracer are assumed here.
This implies:
$dV_L/dt = 0$ and $dC_L/dt = 0$
Therefore, Equations 2 and 3 can be given as:

$$G_i - G_o = S_o + E_{ol} - S_i - P_l = 0 \quad (4)$$

$$C_{Gi} \times G_i - C_{Go} \times G_o = C_{So} \times S_o + C_{Eol} \times E_{ol} - C_{Si} \times S_i - C_{Pl} \times P_l \quad (5)$$

The chloride content of the evaporating water flux is zero and the term $C_{Eol} \times E_{ol}$ will be eliminated in Equation 5.
The uncertainty associated with the measurement error of the hydrological fluxes used has been calculated in order to see the uncertainty or error bound introduced with the computed groundwater inflow and outflow, using Equation 6.

$$Error = [(eP_l \times P_l)^2 + (eE_{ol} \times E_{ol})^2 + (eS_i \times S_i)^2 + (eS_o \times S_o)^2]^{0.5} \quad (6)$$

Where, e with the respective subscripts show error associated with each parameter. eP_l, eS_i and eS_o are taken to be 5% (Kuzmin et al. 1974) while eE_{ol} is taken to be 10%.

4. Results

4.1 Estimated Hydrometeorological Data

The hydrometeorological data inputs processed and estimated as described in Section 3.1 are given below (Tables 1 and 2). These data are used to estimate recharge and lake balance evaluations.

4.2 Estimation of Recharge

4.2.1 Base Flow Separation

The total river flow is partitioned into base flow and direct runoff using BFI values of each station. BFI varies from place to place depending on the geomorphology and hydraulic characteristics of the formation covering the area. Figure 4 shows the total and groundwater base flow hydrographs for Gilgel Abay river station.

The mean base flow or shallow groundwater recharge rate has been estimated as weighted average by area of base flows of all stations to be 195.6 mm/year. Table 3 shows BFI, direct runoff and base flow values. The main purpose of base flow analysis is to estimate the mean rate of groundwater recharge or discharge as base flow (Rutledge and Mesko 1996). However, the actual mean groundwater recharge rate exceeds the base flow or groundwater discharge to streams by the amount equal to the sum of riparian evapotranspiration from groundwater and stream channel, conceptive use in upstream areas, and deep recharges that underflow beneath the streams' beds.

The recharge value estimated by this method therefore indicates the minimum recharge rate of the shallow aquifer, which interact with surface waters, for the whole volcanic terrains including un-gauged catchments excepting the flat plain in eastern and northern parts of the area where the streams are influent to the groundwater here.

4.2.2 Soil Water Balance

Soil water balance computation was done using the above described method (Section 3.2.2) and the data given in Table 1. Book keeping of mean monthly basin precipitation, direct runoff, and crop evapotranspiration and soil moisture accretion has given recharge rate of 285.4 mm/year. Table 4 depicts the data used and the results of soil water balance computation. This recharge value is a reasonable estimate of the net basin recharge reaching the groundwater table as the direct runoff used in the calculation incorporates the interflow values, and because seepage or through flow that emerges at nearby foot slopes generally has small magnitude.

4.2.3 Chloride Mass Balance

The following values have been used for recharge estimation based on chloride mass balance method (Section 3.2.3).
P= 1400.4 mm/year
C_p=1.2 mg/l
Q= 440.7 mm/year
C_q= 2.12 mg/l
C_{gw}= 2. 63 mg/l

These data have been inserted into Equation 1 and computation has given a recharge rate of 284.0 mm/year. The result shows effective recharge that joins the groundwater reservoir. Isotopic data under this study revealed diffuse groundwater recharge during rainy summer season, which suggest no major recharge through preferential flow. Therefore, the recharge water can get time to evaporate in weathered mantle of the volcanic aquifers so that the recharge estimated by CMB does not overestimates and represents the actual mean recharge rate in the basin.

4.3 Tana Lake Balance

The following values for fluxes and Cl concentration have been used for the parameters set in Equations 4 and 5.

P_l= 4016 hm^3/year
C_{Pl} =1.19 mg/l
E_{ol} = 4720.3 hm^3/year
S_i-gauged = 4207.3 hm^3/year (excepting Gelda station data)
S_i- un-gauged = 2278.3 hm^3/year
C_{Si} = 2.97 mg/l
S_o = 4733.4 hm^3/year
C_{Gi} = 82.9 mg/l

The chloride content of the lake (Cl = 2.87 mg/l) has been assigned to surface water outflow (S_o) and groundwater outflow or leakage (G_o).

Therefore, solving Equations 4 and 5 has given groundwater outflow or leakage rate of 954.8 hm^3/year, and groundwater inflow of -93.1 hm^3/year. The groundwater inflow value is negative but small, which is within the limit or error bound introduced in the estimate due to measurement error of the hydrological fluxes. This suggests that there is no significant direct groundwater contribution to the lake.

River water loss to recharge the lacustrine sediments aquifer in the eastern and northern plain areas seems generally to be small that does not significantly alter the results, and it was not accounted in the lake balance evaluation.

Uncertainty or error bound of ±375.0 hm^3/year, which is propagated from measurement error to the estimated groundwater inflow and leakage outflow values, is calculated based on Equation 6. The hydrochemical data have electro neutrality less than 5%, which indicates acceptable accuracy that does not introduce significant error in the estimates.

Sensitivity Analysis

Sensitivity analysis has been done by varying the fluxes and Cl concentrations to see their influence on the derived G_o and G_i . G_o and G_i have been calculated for the range of ±20% Cl contents of precipitation, groundwater inflow and the Tana Lake, and for evaporation and un-gauged runoff fluxes. Table 5 depicts the percentage change on leakage rate and groundwater inflow for the changes of the respective input parameters.

Sensitivity analysis showed that the groundwater inflow estimate is highly susceptible and influenced by Cl content of the lake followed by evaporation rate. Change in Cl content of the groundwater inflow and precipitation have relatively less impact on the estimated groundwater inflow.

Leakage rate is highly sensitive to the lake evaporation rate and to lesser extent to un-gauged runoff while the change in other input parameters has generally low influence on it.

5. Discussions

Most previous works concluded the Lake Tana basin as closed system in terms of basin groundwater inflow and outflow, and groundwater inflow to and outflow from the lake were considered to be negligible. Furthermore, the conclusions about interaction between streams and groundwater were contradictory.

Different methods can be employed to estimate groundwater recharge rate in the area. Previous attempts mainly used hydrograph separation methods and only one have used chloride mass balance method, which did not take into account the surface runoff. Recharge rate of 184.3, 161.7, 70-120, 142.7 mm/year have been estimated by Sogreah (2012), Getachew (2010), Getachew (2008) and BCEOM (1998), respectively.

However, hyderogeological, hydrogeochemical and isotopes data in this study have shallow groundwater circulation in unconfined aquifer and deep base flow in confined aquifer, which are interacting through fractures. The shallow groundwater interacts with the streams and Tana Lake. Hence, groundwater recharge estimation based on only by river hydrograph separation does not give the real recharge rate taking place.

It under estimates the recharge by the amount equal to the riparian evapotranspiration, consumptive uses in upstream areas and deep groundwater recharge. Recharge rate has been estimated in this study using base flow separation, soil water balance and chloride mass balance methods.

Base flow analysis gave mean recharge of 195.6 mm/year. The result is in agreement with the results of Samson (2010), Sogreah (2012) and Getachew (2010). Other previous studies underestimate the groundwater base flow to streams.

Base flow separation method shows recharge to shallow aquifer that returns to and sustain the rivers flows as groundwater discharge or base flow. Most of the streams and major rivers are perennial and there are frequent springs and shallow hand dug wells with groundwater head above the streams' water level suggesting that the streams are fed by groundwater.

Soil water balance and chloride mass balance on the other hand have given net recharge rates of 285.4 and 284.0 mm/year, respectively. The results of these two methods are reasonable and nearly similar despite the fact that the methods are different. This is because the effect of interflow and seepage on the estimated recharge from soil water balance is negligible or low. The interflow component of the river hydrograph has also been incorporated in the direct runoff that was used in the soil water balance computation (Table 4).

Furthermore, the recharge is not a preferential flow via fractures but has passed through soil and weathered zones of volcanic aquifers where the recharge water has got time to evaporate before reaching the water table so that the CMB method does not over estimate the recharge. Diffuse recharge through the soil and weathered zone of the volcanic aquifers has been revealed to take place by isotopic data.

The mean recharge of the basin, which includes the shallow and deep ground waters recharges, can then be taken as the average of recharge estimated by soil water balance and chloride mass balance methods, which is equal to 284.7 mm/year. It accounts to 20.1 % of the basin precipitation.

The groundwater base flow to streams is about 68.7% of the mean basin recharge. The rest 31.3% is deep recharge that does not return to streams and contributes to regional groundwater base flow under the stream beds. Basin water balance evaluation and hydrogeochemical and isotopic data have shown regional deep groundwater basin outflow to Tis Abay area, and this supports the above conclusion.

The fact that most of the recharge contributes to streams has great implication to the groundwater management. The Government has an attempt to develop the groundwater and surface waters for irrigation use. Therefore, medium and large scale development of groundwater will dewater the groundwater reserve, and reduce the flow of streams and inflow to the lake, which adversely affects the existing and proposed irrigation schemes using surface waters and prior and proposed groundwater uses for urban, rural and industrial supply. This will also let the wetland and the lake diminishes, and will have negative consequences on wetland ecosystems, hydropower development and navigation on the lake.

It is therefore better to develop surface waters for irrigation and keep the groundwater resource for other domestic and industrial uses. Groundwater development for irrigation may be considered in sub-catchments where there is no intensive rivers and groundwater developments and where that it does not cause lowering of the regional water table.

Lake balance study here has given leakage rate of 954.8 hm^3/year from the Lake Tana. This gave new insight to the presence of inter basin groundwater outflow and leakage underflow from the lake.

Major leakage underflow from the Lake Tana is via deep lineaments network in its western margin toward the adjacent Beles basin (Figs. 2 and 3). Isotopic tracing and hydrological data of this study revealed mixing of the lake water to the local groundwater in the area. Some contribution of leakage water from the Tana Lake to Tis Abay area, which is through the southern bank of the Lake, also seems to occur.

Lake balance evaluation has given negative groundwater inflow rate (-93.1 hm^3/year) to the lake. The result suggests that there is no major groundwater inflow directly entering to the lake from the surrounding areas (i.e., it is within the limit of uncertainty or error bound) although hydrogeological and hydrogeochemical evidences indicated some groundwater contribution. This agrees with most of the previous authors' conclusion that the groundwater inflow to the lake is negligible. The low groundwater contribution seems to be due to the clayey nature or low permeability of the lacustrine sediments around the lake margin and beneath the lake.

6. Conclusions

In this study, recharge estimation was done based on base flow separation, soil water balance and chloride mass balance methods. Recharge evaluation using base flow analysis gave the groundwater recharge rate of 195.6 mm/year, which discharges as base flow to streams.

On the other hand, soil water balance and chloride mass balance methods although are different approaches have given comparable recharge rates of 285.4 and 284.0 mm/year, respectively, which show the reliability and consistency of the methods to calculate the basin recharge in the area.

Average groundwater recharge of the basin has been estimated to be 284.7 mm/year based on the results of the two methods, which includes the shallow recharge that feeds the streams and deep recharge the contributes to the regional groundwater flow beneath the streams beds.

This shows that large part of the groundwater recharge (68.7%) discharge as base flow to the streams while about 31.3% (89.1 mm/year) is the deep recharge.

Lake balance study has revealed leakage rate of 954.8 hm^3/year from Tana Lake. Leakage water is proved to underflow and mix with the local groundwater in the adjacent low lying Beles basin, and to some extent to Tis Abay area. On the other hand, groundwater inflow directly to the lake has been found to be minor.

Medium and large scale groundwater developments will overdraft the groundwater reserve, and will entail drying of streams flow and shrinking of the lake and wet lands. This will have adverse effect on prior development activities of irrigation using surface waters, on the riparian ecosystems, navigation and hydropower development, as well as on current and future groundwater development schemes for urban, rural and industrial water supply.

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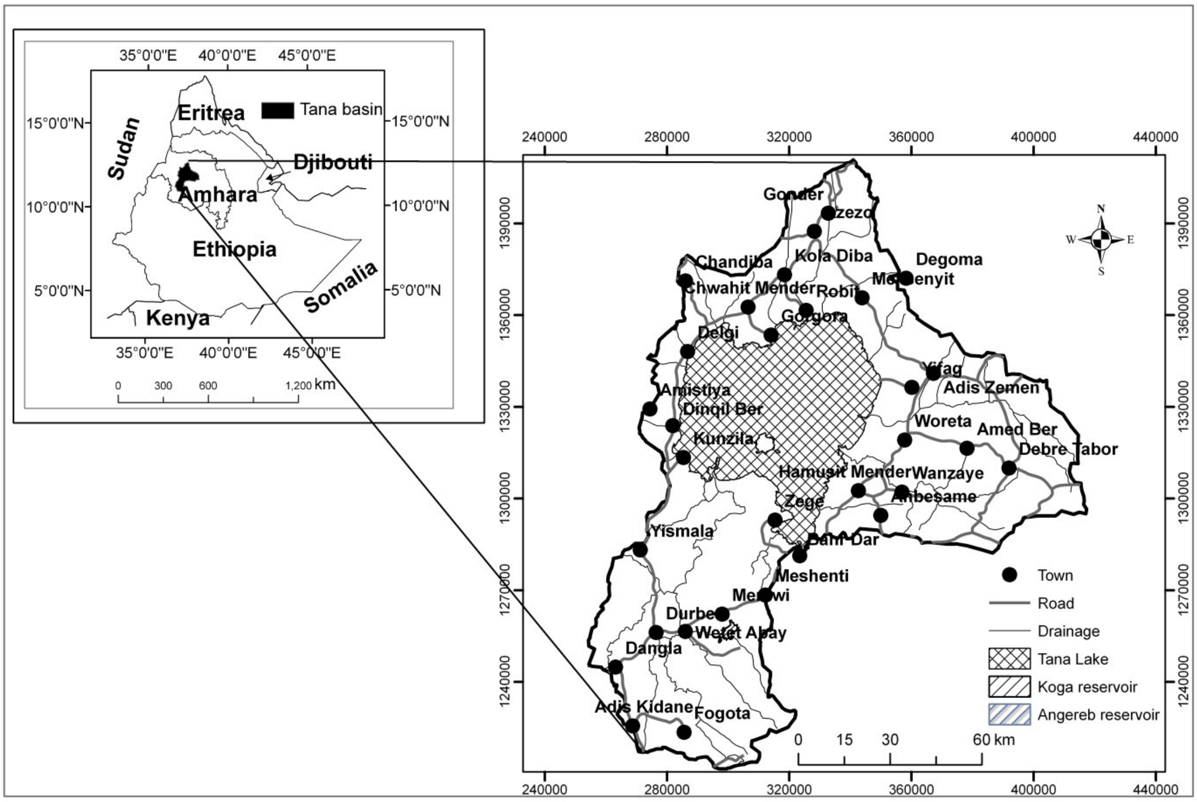

Figure 1. Location of Tana basin

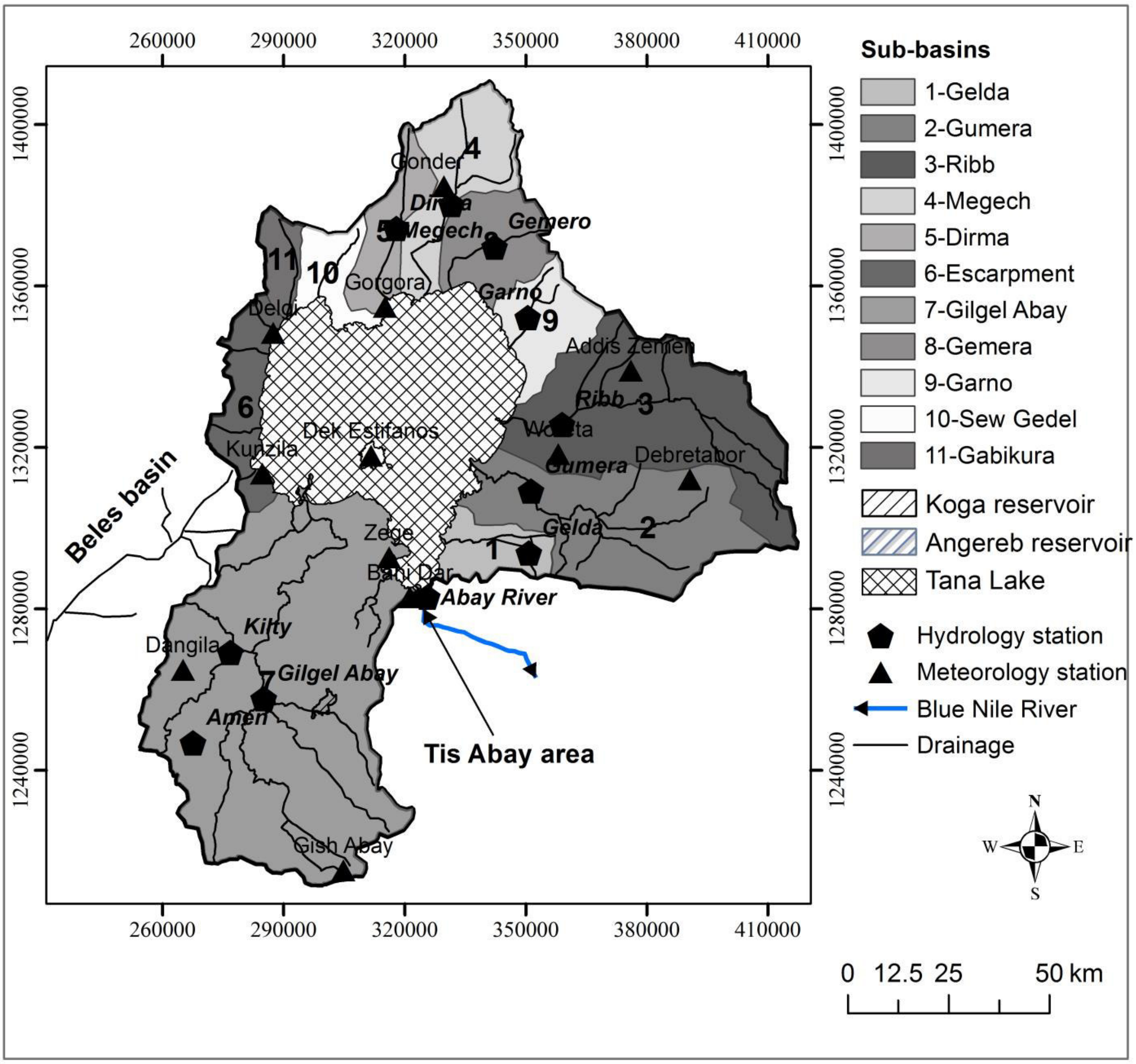

Figure 2. Map showing sub-basins in the area. Labels in italics indicate hydrological stations, other lables for meteorological stations

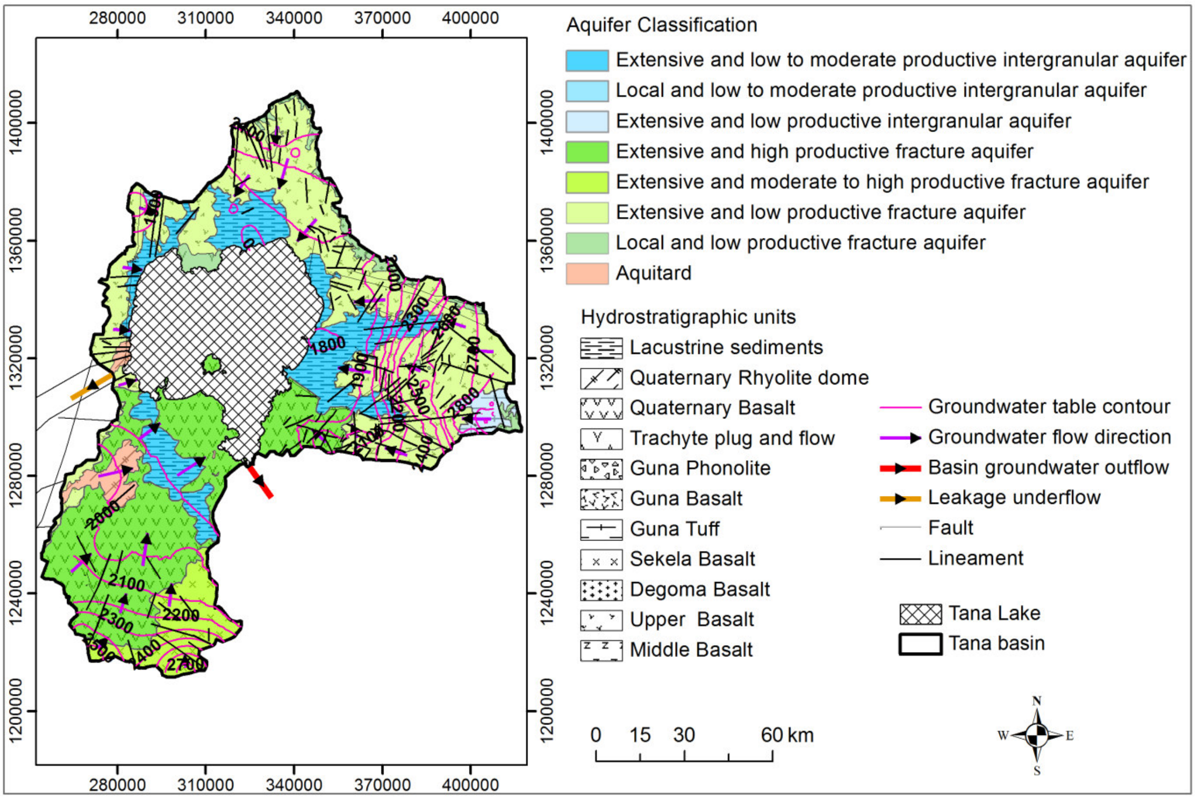

Figure 3. Hydrogeological map of the area

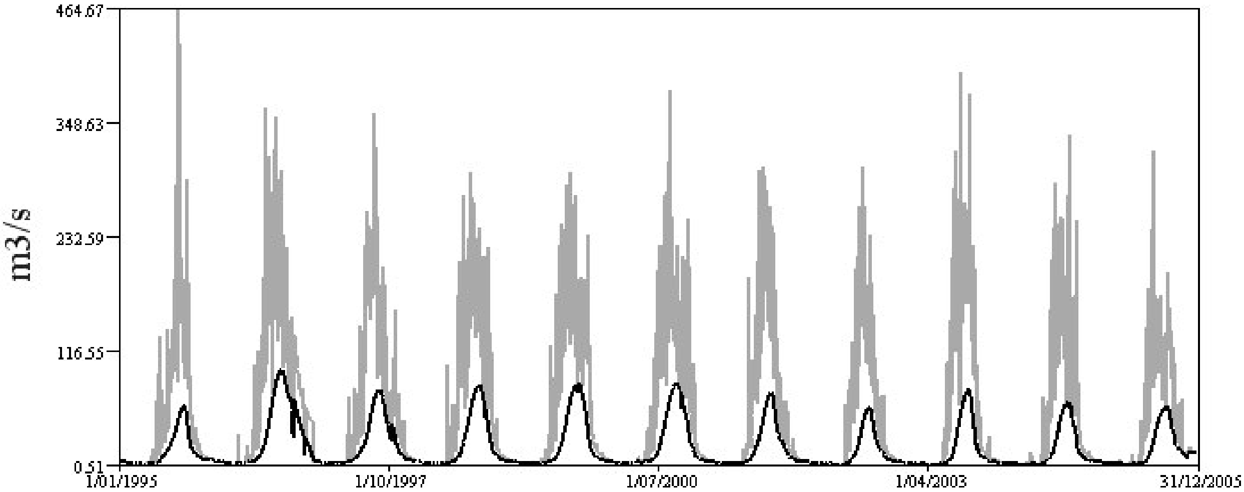

Figure 4. Groundwater base flow (black) and total river hydrograph (grey) for Gilgel Abay river station

Table 1. Estimated mean meteorological parameters for the basin (1995-2009), in mm

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	4.5	3.9	16.4	27.7	88.6	207.9	382.7	358	194.1	91.5	15.8	9.5	1400.4
ET_o	110	120	138	136	131	103	85	84	102	110	103	103	1329
E_{ol}	129.0	145.7	168.1	191.8	159.4	95.6	94.0	93.4	113.7	108.5	125.4	118.9	1543.9
E_{osm}	3.1	2.7	11.2	19.0	60.7	94.2	74.8	93.4	113.7	108.5	125.4	57.6	764.2
E_{opm}	129.0	145.7	168.1	191.8	159.4	95.6	94.0	93.4	113.7	108.5	125.4	118.9	1543.9
AET	3.1	2.7	11.2	19.0	60.7	94.2	74.8	73.9	89.8	96.8	90.7	57.6	674.4

P: precipitation, ET_o: reference potential evapotranspiration, E_{ol}: lake evaporation, E_{osm}: evapotranspiration from seasonal marsh, E_{opm}: open evaporation from permanent marsh, AET: actual evapotranspiration

Table 2. Mean gauged and un-gauged total runoff (hm3/year)

Streams	Gilgel Abay	Kilty	Dirma	Gumera	Ribb	Gelda	Garno	Gemero	Megech	Un-gauged runoff	Abay River
Discharge	1691.4	276.5	235.5	1208.4	493.4	49.0	26.5	48.2	227.4	2260	4733.4
Calculated gauged area (km^2)	1946.7	595.3	377.0	1189.7	1704.5	35.6	102.2	184.4	518.6	5134.1	14845.5

Table 3. Recharge estimate based on base flow separation method

	BFI	Total flow (mm)	Base flow (mm)	Direct runoff (mm)	Catchment area (km^2)	DRO*Area	Base flow*Area
Ribb	0.282	289.5	81.6	207.8	1704.5	354273.3	139143.5
Megech	0.333	438.4	146.0	292.4	518.6	151644.6	75708.6
Kilty	0.305	464.5	141.7	322.8	595.3	192165.1	84331.5
G/Abay	0.326	868.9	283.3	585.6	1946.7	1140023.3	551405.9
Garno	0.414	259.3	107.3	151.9	102.2	15527.4	10969.9
Gemero	0.21	261.4	54.9	206.5	184.4	38074.4	10121.0
Gumera	0.289	1015.7	293.5	722.2	1189.7	859148.2	349217.8
Total					6241.4	2750856.4	1220898.2
Weighted mean DRO and base flow (mm/year)						440.7	195.6

DRO: Direct runoff

Table 4. Soil water balance (mm); available water capacity 165 mm

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	4.5	3.9	16.4	27.7	88.6	207.9	382.7	358.0	194.1	91.5	15.8	9.5	1400.4
DRO	1.4	1.2	5.2	8.7	27.9	65.4	120.4	112.7	61.1	28.8	5.0	3.0	440.7
ET_O	110.0	120.0	138.0	136.0	131.0	107.0	85.0	84.0	102.0	110.0	103.0	103.0	1329.0
ETc	96.8	105.6	121.4	119.7	115.3	94.2	74.8	73.9	89.8	96.8	90.6	90.6	1169.5
Sm	0.0	0.0	0.0	0.0	0.0	48.3	165.0	165.0	165.0	130.9	51.1	0.0	
dSm						48.3	116.7			-34.1	-79.8	-51.1	
AET	3.1	2.7	11.2	19.0	60.7	94.2	74.8	73.9	89.8	96.8	90.7	57.6	674.4
R	0.0	0.0	0.0	0.0	0.0	0.0	70.8	171.4	43.3	0.0	0.0	0.0	285.4

Sm: soil moisture, dSm: change in soil moisture, R: recharge

Table 5. Percentage changes in G_o and G_i for the changes in the respective input parameters by ±20%

Parameters	Change of the calculated parameter (%)*	
	G_o	G_i
Cl content of precipitation	-1.3/+1.3	-12.9/+13.0
Cl content of groundwater inflow	+1.7/-2.5	+17.2/-26.1
Cl content of Tana Lake water	+4.0/-4.2	+40.7/-43.2
Evaporation	-102.4/+ 102.4	-36.3/+36.4
Un-gauged runoff	+47.7/-47.9	-0.5/+0.6

* The numbers in the columns correspond to the increase/decrease by 20% of the respective input parameters