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Water Balance for Mbagathi Sub-Catchment

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ABSTRACT

Increasing water demands with limited supplies is a concern for agencies charged with its provision while observing equity and fairness. This paper aimed at calculating a simple water balance by equating water supplies to the demands in Mbagathi sub-catchment. Groundwater recharge was estimated using the soil water balance method while surface water supplies used Mbagathi river discharge data from stream-flow gauge stations 3AA04, 3AA06 and 3BA29. Survey data collected in 2015 using snowballing approach was used to quantify water demands. Change in groundwater storage in 2015 and 2014 was significantly ($p \leq 0.05$) lower at -0.4 and 1.3 million m^3 respectively, compared to 2013, 2012, 2011 and 2010 at 9.9, 11.9, 14.6 and 22.6 million m^3, respectively. Reductions in groundwater storage from 2010-2015 were attributed to rise in demand, inefficient use, climatic variations characterized by low rainfall to recharge aquifers and limited exploitation of polished wastewater in the study area. Unsustainable water availability amidst over-reliance on groundwater and dominance in domestic and agricultural uses was observed in Mbagathi sub-catchment necessitating drastic water management measures. The study concluded that adopting water use efficient practices such as water harnessing, water re-use, soil and water conservation measures could ease pressure on existent supplies.

Keywords: Groundwater; surface water; water demand; water supply; Mbagathi sub-catchment

1. INTRODUCTION

A catchment water balance is an assessment of outputs (demands) and inputs (supplies) to understand the functioning of surface water, its hydrological setting and the sustainability of groundwater (Dingman, 2002). The water balance equation of a watershed deducts the outputs; ground- and surface-water abstractions, river discharge and evapotranspiration from the inputs that include rainfall and groundwater inflow to get storage changes Eq. 1.

$$I = O - \Delta S \qquad 1$$

Where I denote the water inputs consisting of rainfall and groundwater flow, O are the outputs including river discharge, evapotranspiration and abstractions and ΔS indicates water storage changes that give the balance and should be stated as either positive or negative.

The ΔS concept equates water availability and demands to plan on water allocation priorities for efficient use amidst concerns of increased demand, climate variability and change (Combalicer et al., 2008; Tripathi et al., 2005; WRMA, 2015). Assessment of changes in water storage is important as it determines opportunities, landscapes and climatic features for optimal human land uses (Shiklomanov, 2005). In Lake Naivasha basin, Kenya (Becht, 2007) and Juba-Shabelle river basin, Ethiopia (Sebhat, 2014), water balances enabled systematic accounting of water with reference to end uses and products. Studies carried out in

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Mbagathi sub-catchment have not highlighted clearly on the sensitivity of available water to historical and future climate conditions that would relate area water storage, runoff, drainage and seepage to hydrologic processes and climate inputs. In addition, the sub-catchment has limited data on monitoring and control of water variability thus necessitating water balance calculation. To try and resolve water challenges, this study focused on calculating a simple water balance for Mbagathi sub-catchment. This is a preliminary study due to limitations of data availability and non-existence of related studies in the area.

2. MATERIALS AND METHODS

2.1 Location of study area

The study was conducted in Mbagathi sub-catchment of Athi catchment, which traverses Nairobi, Kajiado and Machakos counties and is situated in North-South grid 240000-269000 and East-West grid 9855000-984300. The sub-catchment covers an area of 166 km^2 and has Mbagathi as its main river. The river originates from Ngong hills at an altitude of 1980 meters above sea level and flows through the industries to Athi River town then joins Athi River to Indian Ocean (Kihara, 2002; Krhoda, 2002). Fig. 1 shows a map of the study area.

Rapid population growth and unplanned settlements have resulted to land degradation upstream of the sub-catchment negatively affecting the quantity and quality of its fresh water resources downstream. Inter-tropical Convergence Zone (ITCZ) controls the climate of the area, as in most parts of Kenya, as the winds and pressure belts shift (FAO, 1998; Karuku et al., 2014).

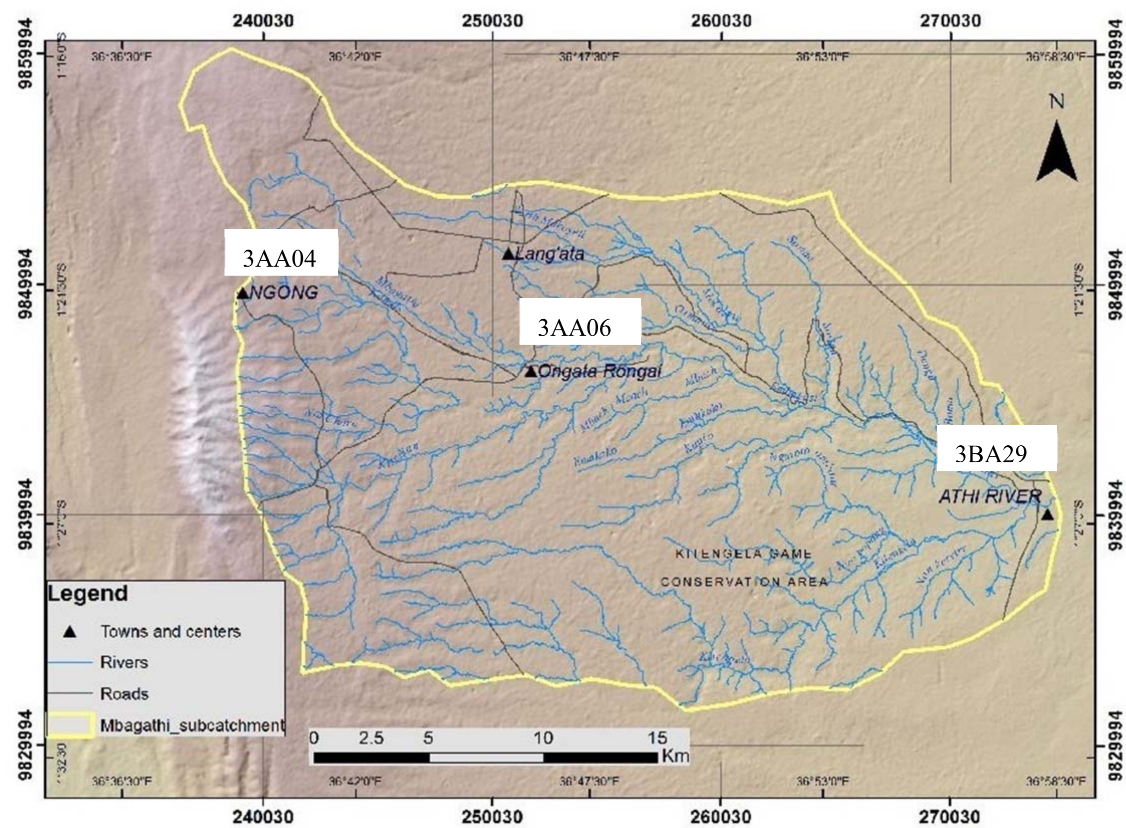

Figure 1 Map of Mbagathi sub-catchment (Nyika, 2017)

2.2 Research design

The study used primary and secondary data to evaluate the water balance for Mbagathi sub-catchment. Data collection was categorized into supply and demand whereby the former, was sub-divided into ground- and surface-water supplies. Groundwater supply was calculated using the soil-water balance method as shown in Eq. 2:

$$R = P - Q - ETo \quad (2)$$

Where R is the groundwater supply (m^3), P the total rainfall falling on the sub-catchment in a year (m^3), Q the runoff (m^3) and ETo the potential evapotranspiration (m^3).

Runoff and rainfall mean data of 6 years were determined using secondary data obtained from Kenya Meteorological Department at Dagoretti Corner Station (No. 9136164) and converted to volume using Eq. 3 and 4, respectively from the MoWI design manual (2005).

$$Q = \frac{F \times A \times R}{1000} \quad (3)$$

Where Q is the annual runoff (m^3), F the catchment runoff coefficient (0.3 for Athi water catchment), A the catchment area (m^2) and R the mean annual rainfall (mm).

$$P = \frac{A \times R}{1000} \quad (4)$$

Where P is the total rainfall falling on the sub-catchment in an average year (m^3) A and R as above Eq. 2.

Potential evapotranspiration was calculated using the Hargreave's (1994) method as shown in Eq. 5.

$$ETo = 0.0022 \times RA \times (Tc + 17.8) \times TD^{0.5} \quad (5)$$

Where ETo is the potential evapotranspiration (mm), RA the extra terrestrial radiation in Joules per meter squared per day ($J/m^2/d$), Tc the mean temperature in ^oC and TD the difference between maximum and minimum mean temperature in ^oC. The results were converted to m^3 using Eq. 4.

Surface water supplies from Mbagathi river were estimated from average discharge rates recorded in stream-flow gauge stations: -3AA04, 3AA06 and 3BA29 (Fig. 1) from 2010-2015. Water Resources Management Authority (WRMA) provided the secondary data for the three stations that were representative of the sub-catchment's main river and their average provided its discharge annually.

Ground- and surface-water demands in 2015 were estimated in a survey of 716 respondents selected through a snowballing approach. A two-step survey approach involving mapping the formal network structure of water users in Mbagathi sub-catchment by listing all users in WRMA's database then asking them to identify others not listed to give additional water users was employed. For the purpose of this study, household heads and industry operations managers were interviewed individually using a pre-structured questionnaire on the sources and amounts of water used daily in litres, which were then converted to m^3. The results were compared with secondary data of 2010-2014 from WRMA databases. Ground- and surface-water storage changes in the sub-catchment were obtained by deducting total demands from supplies and reported as positive or negative balance.

Data obtained on water supplies, demand and storage change was subjected to ANOVA and mean separated using LSD to compare the means of treatments and their interactions. The statistical significance referred to $\alpha = 0.05$ unless otherwise stated. Percentages were used to compare ground- and surface-water supplies.

3. RESULTS AND DISCUSSIONS

3.1 Groundwater supply

Groundwater supply in the study area for 2010 to 2015 is shown in Table 1. Groundwater supply ranged from 29.6 to 12 million m^3 between 2010 and 2015. Significantly ($p \leq 0.05$), lower amounts of groundwater supply were calculated at 12 and 14.4 million m^3 in 2015 and 2014, compared to 22.2 and 29.6 million m^3 in 2011 and 2010, respectively. Observed reductions in groundwater supply could be because of decrease in rainfall (P) and low aquifer recharge in 2014 and 2015 compared to 2011 and 2010 when rainfall was high. These observations could point to climate variation effects in the area despite increased demand with increasing population. Climate variation and change influenced groundwater availability in the study area. In Upper Sheep Creek watershed, USA (Flerchinger and Cooley, 2000) and Karangmumus watershed, Ghana (Sujalu et al., 2014), reductions in groundwater supply were a result of low rainfall hence inadequate groundwater recharge.

Significantly ($p \leq 0.05$), higher amount of rainfall at 43.44 million m^3 was recorded in 2010 compared to 21.5 and 15.8 million m^3 in 2014 and 2015, respectively. This observation could be because of climate variability characterized erratic rainfall patterns usually lower than expected in the long and short rainfall periods. Consequently, there are reductions in groundwater that rely on rainfall for recharge. In Ethiopian (Calow and MacDonald, 2009) and Malawian (Delude, 2010) basins, historical reviews of climate patterns over a period of 10 years since 2000 attributed reducing rainfall to unpredictable weather patterns amidst variable climate.

3.2 Surface water supply

Mbagathi River supplied the sub-catchment with surface water (Table 1). River flow increased gradually and was significantly ($p \leq 0.05$) higher at 7.5, 7.1 and 7.0 million m^3 in 2015, 2014 and 2013, respectively compared to 4.2, 3.8 and 2.7 million m^3 in 2012, 2011 and 2010, respectively despite reductions in rainfall during the 6-year period. Observed increases in stream-flow could be due to increased pollution of the river from raw industrial effluent disposal rendering its waters unsafe for use and reducing the amount of withdrawals done on it for consumptive uses. Increased runoff from pavement construction in the sub-catchment's urban areas, which reduced infiltration explain observed increases in discharge despite the reductions in rainfall over the years. In Nairobi metropolitan where Mbagathi sub-catchment is located, the rate of urbanization increases by an average 5.2% every year leading to a 12% increase in construction of overcrowded, paved and impoverished informal settlements (Ngayu, 2011). Consequently, water infiltration is becomes impossible and water drains to rivers increasing their total flow. In Kenya (Booth and Bledsoe, 2011) and Korea (Im et al., 2007), urban areas have been observed to increase runoff to rivers by 6.5% yearly due to construction of impervious surface covers and pollution of rivers. Similar observations were made in USA (Meyer and Wallace, 2001; Paul and Meyer, 2001) whereby paving over and placing culverts on waterways increased runoff and ultimately, stream-flow in Colorado River. Observed stream-flow rise could also be attributed to increased runoff and erosion in the sub-catchment resulting from vegetation clearing for human settlement. Increased erosion prevents infiltration and percolation of water by forming hard pans forcing the water to escape as runoff especially if there is no vegetation cover to hold water. Human settlement also blocks infiltration spaces and facilitates generation of runoff. In Mara (Mati et al., 2008; Mutie et al., 2006) and Gucha

(Kathumo, 2011) sub-catchments in Kenya, rising river discharge was attributed to vegetation clearing for human settlement that resulted in increased runoff and erosion.

3.3 Comparison of ground- and surface-water supplies

Fig. 2 compares calculated ground- and surface-water supplies in Mbagathi sub-catchment from 2010 to 2015. In the six years, groundwater supply was at least 60% of total available water though the lowest contribution of the resource was in 2015 at 61.6% compared to 2014, 2013, 2012, 2011 and 2010 at 66.8, 74.7, 82.9, 85.4 and 91.7%, respectively. This trend points to climate variability characterized by low rainfall and resource over-exploitation due to a possible rise in demand from the growing population leading to over-pumping without adequate groundwater recharge in the sub-catchment. Californian basins (Kenny et al., 2009) are reported to experience groundwater depletion due to resource over-abstraction owing to population increase leading to inadequate aquifer recharge.

Table 1 Groundwater supplies and river discharge in Mbagathi sub-catchment

Year/ Parameter	P ($\times10^6$ m^3)	Q ($\times10^6$ m^3)	ETo ($\times10^6$ m^3)	Total Groundwater supply($\times10^6$ m^3)	Mbagathi river discharge ($\times10^6$ m^3/year)
2015	15.8^a	3.2^c	0.6^d	12.0^c	7.5^a
2014	21.5^a	6.4^c	0.7^d	14.4^c	7.1^a
2013	29.5^a	9.2^c	0. 6^d	19.7^a	7.0^a
2012	30.0^a	9.0^c	0.6^d	20.4^a	4.2^b
2011	32.5^a	9.8^c	0.5^d	22.2^a	3.8^b
2010	43.4^b	13.0^c	0.8^d	29.6^a	2.7^b
Mean	28.8^a	8.4^c	0.6^d	19.7^a	5.4^b

Note: Mean figures followed by similar letters a, b and c along columns are not significantly different at p=0.05 during data analysis using ANOVA; P is annual rainfall falling on the sub-catchment; Q is the runoff; ETo is the potential evapotranspiration.

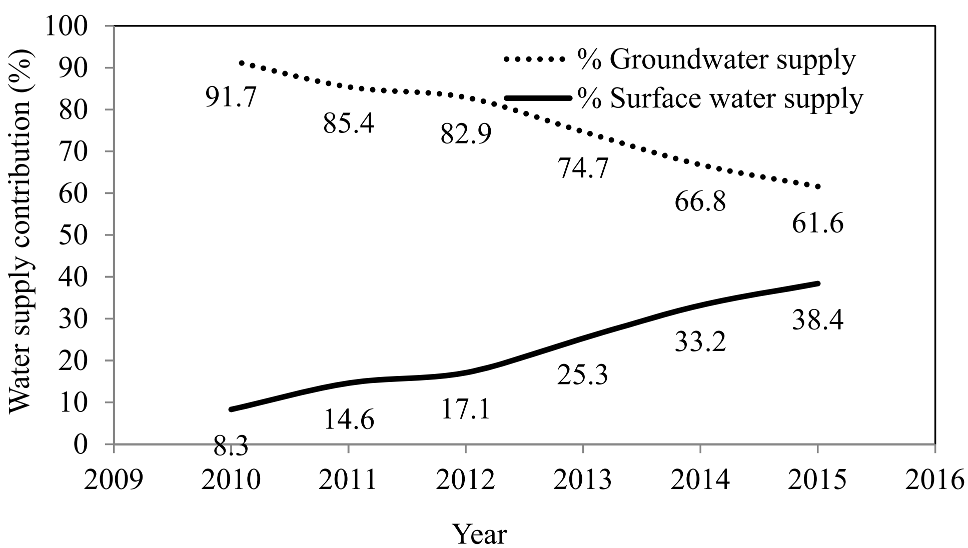

Figure 2 A comparison of ground- and surface-water supplies in Mbagathi sub-catchment

Surface water contribution gradually increased from 8.3 to 38.4% between 2010 and 2015. The trend could be explained by high runoff in the catchment resulting from paving over waterways and vegetation clearing in the area for human settlement. In Njoro River, Kenya (Baldyga et al., 2007), stream-flow increased gradually since 2005 due to change in precipitation characteristics whereby rainfall intensity was higher and infiltration surfaces were paved with culverts. This increase in water availability could also be due to pollution of the stream-flow, therefore rendering it unsafe and less preferred for consumptive uses. According to Gichuki (2014), pollution of Mbagathi river by Ongata Rongai Township upstream and industries in Athi river town rendered the water unsafe for consumption and reduced the total yearly withdrawals by 25%. Additionally, residents turned to groundwater use as an alternative hence the reported reductions in its levels. In Mumbai city, India, Poise River water increased between 2008 and 2012 since withdrawals had reduced after it became polluted by raw domestic and industrial effluent disposals (Chatterjee, 2016).

3.4 Water demands

Using a household survey conducted in 2015, water demands in the study area were identified as commercial farming, domestic use, subsistence farming and industrial use as shown in Table 2. Commercial farming and domestic water uses were significantly ($p \leq 0.05$) higher at 8.9 and 5.5 million m^3, respectively compared to subsistence and industrial uses at 2.5 and 1.6 million m^3, respectively. This observation could be because of a growing population with increased food requirement and the role of agriculture as an economic pillar in the sub-catchment. As such, food security and nutrition as well as income generation dictates water use trends in the area.

Fry (2006) and UNESCO (2003) reported similar findings where more than 90% of water was used to meet agricultural and domestic needs of the rising population in developing countries. Similar evidence was documented in South Africa (Goldblatt, 2004), Libya (Wheida and Verhoeven, 2007) and Texas, USA (Kenny et al., 2009) where commercial farming and domestic water uses consumed over 60% of the total available resource. In Tanzania (Kashaigili, 2010), India (ADB, 2007), Argentina (Jordan et al., 2010), and Kenya (Kundell, 2008), economic development pressures were reported as reasons behind increased water use in commercial agriculture.

As such, many users relied on water for their livelihoods in the agricultural sector. Commercial farming and domestic groundwater uses were significantly ($p \leq 0.05$) higher at 5.9 and 3.7 million m^3 compared to subsistence and industrial uses at 1.6 and 1.1 million m^3, respectively. This observation could be because commercial farming was heavy water users in the study area and domestic use increased due the large population of about 2 million people in the area. The two uses required a reliable water source such as groundwater rather than surface water whose credibility had been compromised by pollution. In Kashima plateau basins, Japan, groundwater for domestic and agricultural uses was preferred because of its low vulnerability to pollution compared to river water (Yoshida et al., 2008). Surface water use for industrial purposes in the sub-catchment was significantly ($p \leq 0.05$) lower at 0.6 compared commercial farming, subsistence and domestic uses at 2.9, 1.0 and 1.8 million m^3, respectively. Mbagathi river's low quality water make it unreliable for industrial uses probably explain the observed trend in the study area. In India, Ganga River hardly provides water for industrial processes since it is heavily polluted by industrial effluent and agrochemical disposal (Rai, 2013). The requirement by

WRMA (2015) for industries to reuse water could also explain the observed low preference to both ground- and surface-water for industrial use in the study area.

3.5 Ground- and surface-water storage changes in the sub-catchment

A comparison of water supplies to demands to determine water storage changes (water balance) in Mbagathi sub-catchment is presented in Table 3. Groundwater storage in 2014 and 2015 was significantly ($p \leq 0.05$) lower at 3.1 and -0.4 million m^3 compared to 9.9, 11.9, 14.6 and 22.6 in 2013, 2012, 2011 and 2010, respectively. Observed reductions in groundwater storage could be attributed to climate variation and change characterized by diminished rainfall and low aquifer recharge. In Lokok sub-catchment, Karamoja (IUCN, 2013), groundwater storage reductions were associated with low rainfall. Inefficient resource use leading to wastage, under-exploitation of alternative water sources such as polished wastewater and increased demand due to population rise leading to over-abstraction without adequate aquifer recovery could also be the cause of the observed reductions in groundwater storage. In Incomati, Zimbabwe (van der Zaag and Carmovaz, 2003) and Colorado, USA (Thomas and Hecox, 2013) river basins, groundwater storage reductions were attributed to increased demand, inefficient resource use and its inadequate replenishment.

Table 2 Ground- and Surface-water use in Mbagathi sub-catchment in 2015

Various water uses in the sub-catchment	Groundwater (Million m^3)	Surface water (Million m^3)	Total amount of water (Million m^3/year)
Commercial farming	5.9^a	2.9^b	8.9^a
Subsistence farming	1.6^b	1.0^b	2.5^b
Domestic uses	3.7^a	1.8^b	5.5^a
Industrial use	1.1^b	0.6^c	1.6^b
Mean	3.1^b	1.6^b	4.6^a

Note: Mean figures followed by similar letters a, b and c along columns are not significantly different at p=0.05 during data analysis using ANOVA

Table 3 Comparison of water supplies and demands of Mbagathi sub-catchment

Year	Groundwater Supplies (Million m^3)	Groundwater Demands (Million m^3)	Groundwater storage (Million m^3)	Surface water supplies (Million m^3)	Surface water demands (Million m^3)	Surface water storage (Million m^3)
2015	12.0^a	12.4^a	-0.4^c	7.5^b	7.0^b	0.5^c
2014	14.4^a	11.3^a	3.1^c	7.1^b	6.4^b	0.7^c
2013	19.7^a	9.8^b	9.9^b	7.0^b	5.7^b	1.3^c
2012	20.4^a	8.5^b	11.9^a	4.2^b	5.3^b	-1.1^c
2011	22.2^a	7.6^b	14.6^a	3.8^b	4.7^b	-0.9^c
2010	29.6^a	7.0^b	22.6^a	3.7^b	4.2^b	-0.5^c
Mean	19.7^a	9.4^b	10.3^a	5.2^b	5.6^b	-0.4^c

Note: Mean figures followed by similar letters a, b and c along columns are not significantly different at p=0.05 during data analysis using ANOVA

Limited rainwater harnessing during high flow could contribute to observed deductions in groundwater storage since most water is lost as runoff rather than as aquifer recharge. The water ends up to the oceans where it is not safe for consumptive uses. Additionally, this observation could be because more water is drawn during dry periods when alternative surface water use is limited in availability. In Limpopo basin, South Africa (Ola, 2009), negative values of groundwater storage were attributed to poor water harvesting during high flows, which led to its loss to oceans and subsequent over-abstraction during drought periods.

The results of this simple water balance have limitations, which were beyond the scope of the current study. The study assumed that the sub-catchment's hydrology was static while in reality it is a transient system since its input-output systems are dynamic with consumptive uses and lateral seepage from adjacent areas (Personal Communication). The study also assumed that groundwater flow was independent from surface water; however, being part of Nairobi Aquifer Suite that serves the Athi catchment, the sub-catchment has complex boundaries that are non-identical to those of surface water (WRMA, 2015). Furthermore, the water balance could not entirely capture the interaction between surface- and ground-water depending on recharge and abstraction changes. As such, further studies are needed to ascertain these preliminary findings using advanced techniques.

CONCLUSIONS

Ground and surface-water storage changes in the sub-catchment were calculated to give a simple balance. Groundwater storage changes in the study area were significantly ($p \leq 0.05$) lower in 2015 and 2014 compared to other years due to low rainfall used in aquifer recharge, increased demand from a rising population, inefficient resource use and limited exploitation of alternative sources such as polished wastewater. In 2015, commercial farming and domestic water uses were significantly ($p \leq 0.05$) higher compared to subsistence and industrial uses in the same period. This observation was attributed to growing population, the rising demand for food and economic importance of agriculture in shaping the livelihood of residents in the area. The findings though preliminary necessitate corrective measures such as enforced water use efficiency, conservation and effective demand-supply management through strong water policies to ensure future availability of the resource and ease negative balances. There is need for further studies in the area to ascertain these findings used advanced techniques.

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