Original Research Article||

Groundwater Recharge and Urban Water Balance of Hawassa City, Ethiopia

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Abstract

In urban areas groundwater recharge is not only from rainfall, but also from wastewater generated from different water users and water supply leakages. In this study different natural and urban recharge components that exists in the recharge process of Hawassa city, southern Ethiopia was estimated. The natural recharge was evaluated based on primary and secondary data using water balance equation. Runoff was estimated using Soil Conservation Service – Curve Number (SCS-CN) and evapotranspiration using Simplified Surface Energy Balance Index (SSEBI) against annual average precipitation. The urban recharge was evaluated from all water supplied by providers and in-situ groundwater sources, consumptive uses, supply leakages and onsite wastewater. The average rainfall was 1163mm/yr, of which the average runoff depth throughout Hawassa City was 88.63mm/yr. However, the average runoff depth in the developed part of the city was 108.4 mm/yr and in the rural area 76.5 mm/yr. The average actual evapotranspiration in Hawassa city was estimated to be 841.33 mm/yr. Yet, for the developed city of Hawassa it was estimated to be 683.06 mm/yr and for the undeveloped area 933.94 mm/yr. The high rate of evapotranspiration in the rural area is due to high evapotranspiration from wetlands and agricultural land cover types. Therefore, the average natural recharge and urban recharge of the study area were 233.04 mm/yr and 52.7 mm/yr respectively. The specific urban recharge in the developed urban area was estimated to be 142.78 mm/yr, which is a quality degraded water recirculating in the urban aquifers. This result can not only indicate the depth of water recharge, but also the nature of groundwater quality in Hawassa City, and inspire actions to mitigate water quality deterioration and increase storage.

Key words: Curve number, Evapotranspiration, infiltration, Natural recharge, Urban recharge

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INTRODUCTION

Aquifers are the world's largest reserves of liquid freshwater (Mishra, 2023). The process of urbanization largely alters the hydrological cycle (McGrane, 2016) that might exist in natural environments, which also affects surface and groundwater resources under urban areas. Wakode et al. (2018) identified four impacts of urbanization on the hydrological cycle, including flooding, water scarcity, changes in surface and groundwater regimes, and water pollution. These effects are a result of surface impermeability, increased water demand from various users, surface and subsurface alteration by infrastructure, and water pollution from point and non-point sources.

Rapid urban growth requires the provision of large quantities of water for various uses from surface or groundwater sources (McDonald et al., 2014). This in turn results in high levels of surface or subsurface wastewater discharge, which also pollutes surface or groundwater. This has a major impact on the water balance of urban areas (Foster, 1990).

When assessing the water balance of urban areas, natural and urban aquifer recharge, in-situ and imported/exported water sources, natural and anthropogenic effects on evapotranspiration need to be considered (Lerner, 2003). And all these factors require intensive data, which may not be available. As a result, calculating the water balance of urban areas is complicated and subject to high uncertainties. With rapid urban growth, soil sealing reduces the natural recharge to aquifers, but high levels of water supply from groundwater and/or surface water, with associated leakage from the supply system, industrial effluent and on-site sanitation effluent, will increase urban (indirect) recharge (Morries et al., 2006; Lerner, 2003). Groundwater management in urban areas therefore requires detailed knowledge of the hydrogeological system and adequate methodology for predicting groundwater recharge inputs and source water quality evaluations.

Hawassa City is the capital of the Sidama Regional State and one of the fastest growing cities in Ethiopia. The main source of water for the city is groundwater. Potable groundwater is extracted from wells on the outskirts of the city and distributed throughout the city. In addition, many hand-dug and borehole wells provide water for various purposes within the city. Although soil sealing reduces natural recharge in urban areas, on-site sanitation facilities and leakage from water supply pipes increase water recharge to aquifers. Recirculation and reuse of groundwater degrades water quality (Jjemba et al., 2014). This is common in developing cities such as Hawassa. The groundwater quality analysis in Hawassa City indicates this fact (Alemu et al., 2024a and 2024b). Groundwater management in this city is important because the city is expanding into the area of high-quality groundwater source.

The objective of this study is to identify and analyze the components of groundwater recharge systems in Hawassa City and to estimate the groundwater budget, so that the information can be used to anticipate sustainable groundwater use through an effective and efficient groundwater management plan, taking into account groundwater quality.

MATERIALS AND METHODS

Description of the Study Area

Hawassa City is located in the Lake Hawassa Watershed in the Central Rift Valley of Ethiopia. It is located in the region of longitudes $38^0 28'$-$38^0 33'$ E and latitudes $6^0 58'$-$7^0 05'$ N (Figure 1). The terrain of the region is made up of flat plains and a few volcano mountains, with elevations ranging from 1680 to 2027 meters a.s.l.

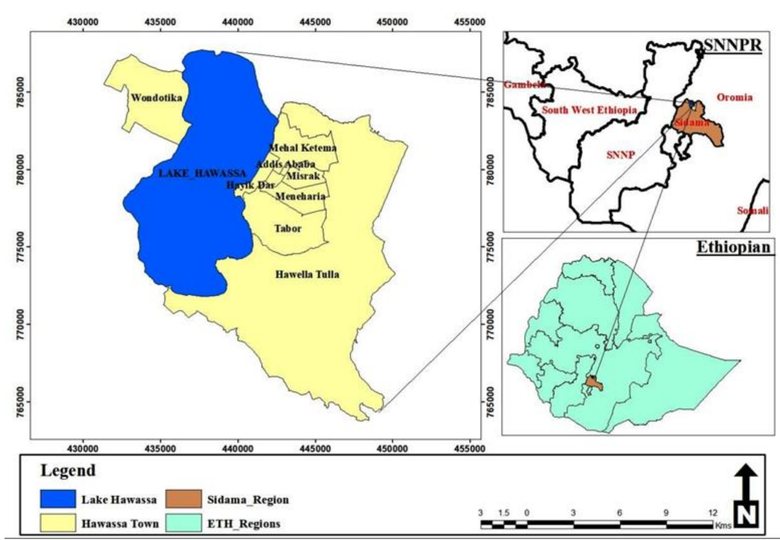

Figure 1. Study Area

The wet and humid months are from April to October. The major rainy season lasts from July to September, and the long-term average annual rainfall is around 954.9 mm (National Meteorological Agency of Ethiopia, 2020). 1,599 mm/year is the potential evapotranspiration (PET). According to NMA, the minimum PET is 102 mm in July and the highest PET is 173 mm in December (NMA). Hawassa City lies on the eastern side of Lake Hawassa. As the lake is the terminal lake of the catchment, the run-off from the city also drains into the lake.

According to Halcrow Group (2009) study, the two main aquifers in the area are the overlaying volcano-lacustrine sediments, and fractured and jointed ignimbrites. Sands, tuff, and pumice are interlayered with clay aquitard in volcano lacustrine sediment aquifers. The lacustrine material is between 40 and 60 meters thick. Boreholes excavated in the lacustrine sediments frequently reveal multiple aquifers divided by clay strata. The most extensive and generally high-quality groundwater aquifer in the main Ethiopian Rift is found beneath faulted tertiary ignimbrites (Hulluka et al., 2023; Halcrow Group, 2009).

Procedures of Groundwater Recharge Analysis

Groundwater recharge in urban areas was estimated by calculating natural recharge from precipitation and urban recharge derived from water supply and leakages from swears networks (Lerner, 2003). Urban groundwater recharge from precipitation could be calculated using water balance equations (Eq.1) such as

$$U_n = P - ET_a - Q_u \qquad \text{(Eq.1)}$$

Where U_n = Natural groundwater recharge, P = Precipitation, ET_a = Actual evapotranspiration and Q_u = Runoff from urban surfaces

Precipitation data was collected from the Hawassa meteorological station for the years (2017-2020), ET_a was calculated from land surface temperature and Penman-Monteith (Filgueiras et al., 2019; Cai et al., 2007) ET_o, and runoff is estimated using the SCS-CN method. The total area of Hawassa city is 154.544 km^2 out of which 55.0737 km^2 is the developed section of the city.

However, urban recharge was calculated from leakage from supply networks, irrigation and sanitation systems. Although it is difficult to find data on leakage because the infrastructure is underground and the processes are not visible, considering the components of the system and analyzing them separately will reduce errors. Lerner (2020) stated that net urban recharge is calculated using (Eq.2).

$$U_u = W_i + GW_a - CU - S_l \quad \text{………. (Eq.2)}$$

Where U_u = Urban recharge, W_i = imported water, GW_a = Local abstracted groundwater, CU= Consumptive use and S_l = effluent leaving the urban area.

In this calculation, the inputs to the system were imported water and locally abstracted groundwater. These components were actually subdivided into the share of different types of users and water lost in the distribution system and unaccounted for water. The consumptive use, portion of consumed water that is embedded in the body of a process parts or is removed from the system in the form of evaporation/evapotranspiration (Grubert et al., 2020); and wastewater transported outside the urban boundary by various users were considered as an output of the system.

In the water balance analysis of Hawassa City, water sources to the city, end use and outputs information from different sources gathered and used. The Hawassa City Water Supply and Sewerage Services Enterprise provide potable water for residential, institutional, commercial and industrial uses. Additionally, many households, service providers, institutions, industries and irrigation farms use their own water supply from underground sources within their premises. At the time of the water sources survey, even though in-situ water source data is not exhaustive it was observed that the total volume of water consumed from private wells was half the volume supplied by the municipal water supply system. Figure 2 shows the distribution of in-situ water supply wells in Hawassa City.

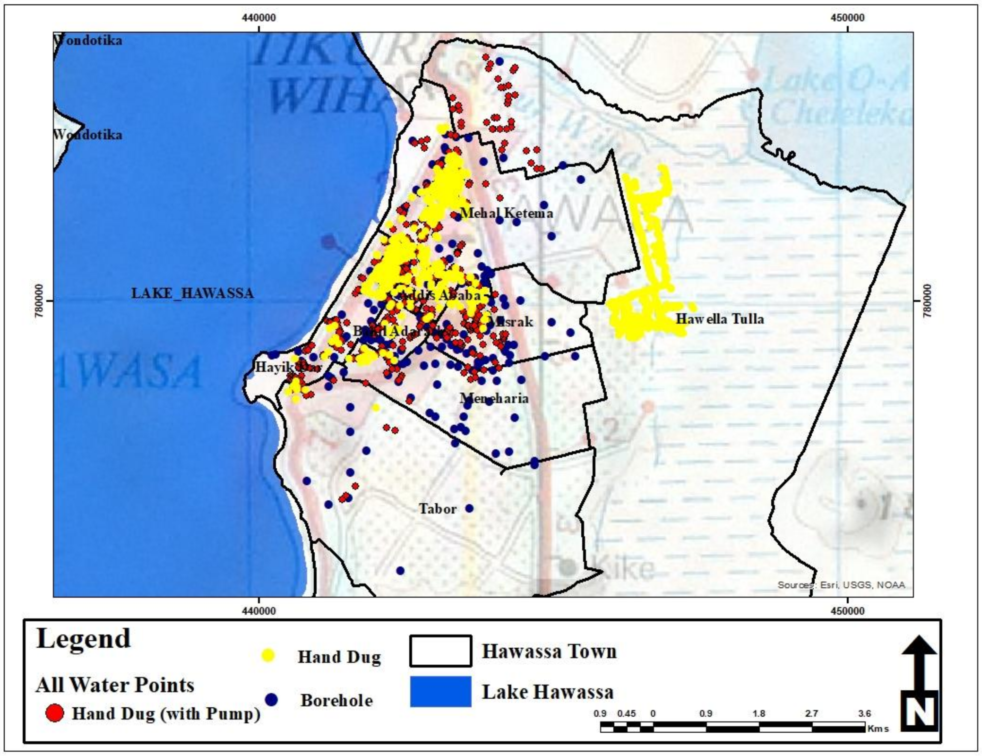

Figure 2. Inventoried in-situ groundwater source points (N = 1579)

Although an inventory was made of the amount of water consumed from onsite water sources, it was not exhaustive, as the inventory depends on the willingness of the well owners. However, the inventory result can indicate the discrepancy between demand and supply of water in the city and is also an important input for the calculation of urban recharge. Since part of the urban population is not supplied with enough water, per capita water consumption cannot indicate the spatial distribution of water supply. Instead, considering the total volume of water supplied to different users and estimating distribution losses will reduce errors (Al-washali et al., 2016). For this calculation, average daily water supply data for different users and expected system losses from the Hawassa Water Supply and Sewerage Service Enterprise collected and used.

The city of Hawassa has no sewerage system and no wastewater treatment plant. Household wastewater includes liquid waste from toilets, baths, showers, kitchens and sinks, which is discharged into a drain. The World Bank (2005) study found that 92% of households reported having toilets that discharged into a tank or pit that was never filled or had to be emptied. This means that the majority of household wastewater is recharging groundwater below the surface. Even the vacuum trucks that collect sewage from septic tanks and latrines dump the waste on sand beds to dewater the sludge for drying on Alamura Mountain, which lies on the outskirts of Hawassa. As the treatment plant is not impermeable and is poorly managed, the potential for aquifer recharge is high. Only a limited number of industries and public institutions have wastewater treatment plants, which fully or partially treat wastewater and discharge it into nearby streams within the city limits. Based on basic assumptions and literature insights, the wastewater discharge and the volume of recharge in Hawassa City aquifers estimated using the following complimentary equations.

The total urban recharge can be calculated by summing all leakage and effluent entering into underground in the urban boundary (Wakode et al., 2018) as (Eq.3).

$$U_u = L_{ws} + L_{dw} + L_{iw} \quad \text{(Eq.3)}$$

Where U_u = urban recharge, L_{ws} = water supply leakage, L_{dw} = recharge from domestic and commercial facilities waste and L_{iw} = recharge from industrial and institutional effluents.
The value was calculated on the basis of expected supply leakage and in-situ effluent discharge after consumption by different water users and from different sources.

The net urban recharge of Hawassa City was calculated from the available data and assumptions as 90% of wastewater discharge plus water supply leakage using (Eq.4).

$$Uu = 0.20*WS + 0.9(WW) \text{ …(Eq.4).}$$
$$0.2*WS = L_{ws}, \text{ and } 0.9*WW = L_{dw} + L_{iw}$$

Where Uu is urban recharge, WS is municipal water supply volume and WW is net in-situ wastewater discharge
Net waste water is calculated as the total waste water discharged by all types of water users minus the waste water discharged outside the city boundary. The natural groundwater recharge component required estimation of actual evapotranspiration and surface runoff within the city boundary.

In urban areas, different land use types with contrasting colors exist within limited areas. This results in different surface albedo and evapotranspiration. Currently, it becomes possible to estimate ET based on remotely sensed data. One of the energy balance methods used to calculate evapotranspiration using remotely sensed data is the Simplified Surface Energy Balance Index (SSEBI) (Wróblewski et al., 2021; Kumar et al., 2020; Senay et al., 2007; Sobrino et al., 2007; Bastiaanssen, 2000; Roerink et al., 2000). Here in this research land surface temperature (Li et al., 2004) was calculated from Landsat 8 image and anchor pixels for hot and cold LST selected. Additionally, sample temperature values for each land cover type collected and average temperature for each land cover type calculated. From the anchor pixels temperature and average temperature for each land cover, the Evapotranspiration fraction (Aryalekshmi et al., 2021; Saboori et al., 2021; Li et al., 2019) calculated using (Eq.5)

$$ET_{fLC} = \frac{Th - T(av-LC)}{Th - Tc} \text{………(Eq.5)}$$

Where ET_{fLC} is ET fraction for particular land cover type, T_h anchor hot pixel temperature, T_c anchor cold pixel temperature and $T_{(av\text{-}LC)}$ average temperature for particular land cover type.
ET_{an} for a particular land cover type is calculated using (Eq.6).

$$ET_{an} = ET_{fLC} * ET_o \text{……………(Eq .6)}$$

Where ET_{an} is actual evapotranspiration for each land cover, ET_{fLC} is ET fraction for the particular land cover type and ET_o is Penmam-Monteith (Cai et al., 2007) ET value.

The actual evapotranspiration of the urban area could be estimated by taking into account the land use class weighting. The formula used for the calculation is (Eq .7)

$$ET_a = \sum_{n=1}^{n} (ETan) * \left(\frac{An}{A}\right) \quad \text{(Eq .7)}$$

Where ET_{an} = actual evapotranspiration for each land use type, A_n = area coverage for each land cover type, A = total area in the urban boundary
The second component needed to determine natural recharge is surface runoff. Urbanization reduces infiltration and increases flow velocity due to changes in surface imperviousness and built structures, resulting in increased ponding and runoff. The Soil Conservation Services Runoff Curve Number (SCS-CN) method was used as it is recommended by the US Department of Agriculture for urban hydrology of small watersheds (Cronshey, 1986). The model takes into account landuse/landcover distribution and soil properties. Basically, the SCS-CN method is based on the water balance equation of rainfall within a given rainfall time interval. The formula used to calculate runoff in the SCS-CN method is (Eq .8).

$$Q = \frac{(P-Ia)^2}{(P-Ia)+S} = \frac{(P-kS)^2}{P+(1-k)S} \quad \text{for } P > kS \text{ and } Q = 0 \text{ for } P \le kS \quad \text{(Eq .8)}$$

Where Q = runoff in mm, P = Precipitation in mm, Ia = Initial Abstraction in mm, S = Maximum soil retention after runoff begins in mm and k = The initial abstraction ratio.

The value of k (initial abstraction ratio) varies from zero to infinity. For the average condition, k is 0.2 and this value has been used by various researchers to calculate runoff, but currently this value is being changed to 0.05 by various researchers (Deshpande and Amit Dhorde, 2023). The Antecedent Moisture Condition (the previous relative moisture of the surface before the rainfall event) was considered by summing the total rainfall that occurred within the previous 5 consecutive days. Three AMC classes were defined based on the total amount of rainfall within the previous 5 days as AMCI (dry), AMCII (normal) and AMCIII (wet) in two (growing and dormant) seasons (USDA, 1986).

The maximum soil retention after runoff starts (S) was calculated and it depends on the hydrological soil group and land cover conditions through the curve number (CN). The curve number has a value between 0 and 100 and the higher the value, the more runoff generation is expected. Four hydrological soil groups A, B, C and D are associated to determine CN, with a soil having a high-water infiltration rate as type A soil and D having the lowest infiltration rate (Kumar et al., 2021). Here gravel and sandy soils are type A and clay soils are type D hydrological soil group. The curve number for each land cover type and hydrological soil group was selected from the look-up table and the weighted CN for the area was calculated from the different LCs. The formula used to convert CN to S is (Eq .9)

$$S = \frac{25400}{CN} - 254 \qquad \text{(Eq .9)}$$

As the curve number shown in the Lookup table is for the normal antecedent moisture condition, it was changed to a CN corresponding to the actual antecedent moisture condition (AMCI or AMC III) and inserted into (Eq .9) above. The formula for converting CNII to CNI or CNIII is (Eq.10) and (Eq .11) respectively.

$$CNI = \frac{CNII}{2.281-0.01281*CNII} \quad \text{or} \quad \text{(Eq .10)}$$

$$CNIII = \frac{CNII}{0.427+0.00573*CNII} \ldots\ldots \text{(Eq .11)}$$

Finally, with the S-value, daily direct runoff from daily rainfall events was calculated using the runoff estimation equation.

Based on the values of daily precipitation, actual daily evapotranspiration and daily runoff, the natural groundwater recharge was calculated using the water balance equation (Eq.1).

The SCS-CN surface runoff estimation method used by (Deshpande and Amit Dhorde, 2023; Hawkins et al., 2008) was adopted to estimate runoff in this manuscript. Based on Deshpande and Amit Dhorde (2023) the initial soil abstraction (Ia) is proposed to be 0.05 of the potential maximum soil retention (S). Using this relationship, the depth of runoff was calculated using the modified (Eq .12).

$$Q = \frac{(P-0.05S)^2}{(P+0.95S)} \qquad \text{(Eq .12)}$$

Components of Urban Water balance of Hawassa City

The water balance provides information on the amount of water flowing into and out of the area under consideration. The water entering Hawassa City from different sources and leaving the city in different forms is considered here. Water entering the city as rainfall, imported water from other catchments as water supply, runoff from upstream of the city boundary, and in situ groundwater extraction are input to the system. Water leaves the city as runoff, wastewater disposal, infiltration into the ground, and evaporation/evapotranspiration. Water balance analysis can help to identify gaps in water demand and supply and the quality of water resources, and to seek possible options to improve gaps and water quality.

Data Sources and Software Used in the Analysis

The data required for this analysis were obtained from, land use/land cover from Wondrade (2023), FAO & IIASA Harmonized World Soil Database version 2.0 (2023), rainfall data from the Meteorological Agency, water supply from Hawassa Town Water Supply and Sewerage Service Enterprise and the researcher's well survey, and various institutional reports and research manuscripts such as Draft Assessment Report" Feasibility Study and Detail Design of Waste Water Management system for Bahir Dar and Hawassa Towns" from Ministry of Water, Irrigation and Electricity and researchers. Google Earth Engine data sources and platform, Arc GIS and EXCEL software were used in the analysis.

RESULTS

Urban recharge and natural recharge were calculated separately, and then the total recharge of Hawassa City was estimated by summing up the two.

Urban Groundwater Recharges Component

Urban groundwater recharge was basically based on the portion of water supply from various sources that enters the urban boundary other than rainfall falling in the area. The sources of water supply to Hawassa City are water supply from Hawassa City Water Supply and Sewerage Service Enterprise, groundwater supply from in situ sources and Lake water supply for Hawassa City greenery by trucks. Although the available data is not exhaustive, the water supply volume shown in the Table 1 used to roughly estimate the recharge volume.

Table 1. **Water Supply types and Volume in Hawassa City (Source: HTWSSSE and Inventory)**

Sr. No.	Source of Water	Volume in m^3/day
1	Municipal water supply	30,000
2	In situ groundwater supply	13,000
3	Truck water supply	1,200

The amount of water supplied is an average and may vary according to the season. Watering for landscaping purposes is applied on a daily basis, especially during the dry seasons of the year. The depth of application is shallow, so that part of the water evaporates or infiltrates into the soil and does not actually reach the groundwater table.

Even the reported amount is far less, as the owners of the groundwater wells were not willing to disclose the amount of water they use; the local groundwater supply is half the amount supplied by the municipal water supply services. In particular, mega water consuming industries in the industrial zone area such as St. Gorge beer factory, Moha beverage factory, textile factory and others were not willing to disclose their water consumption. Out of the collected volume, 3.77%, 11.44% and 84.78% of the water was used by domestic, commercial and services, industrial and public institutions respectively. Industry Park, Hawassa University and Green Herbs Farm were major users of groundwater within their premises. Industry Park has a third stage wastewater treatment plant and a large volume of wastewater is recycled and reused. Hawassa University has an oxidation pond to partially treat wastewater and discharge the water within the campus.

Green Herbs Farm produces vegetables and herbs using drip irrigation in a shaded area. Domestic, and Commercial and service provider in situ groundwater users used the water for non-consumptive purposes and discharge the effluent into septic tanks or soak away pits, which can infiltrate into the groundwater. From the feasibility study report of the Ministry of Water, Irrigation and Energy (MWIE, 2018), 10% of the pits and septic tanks are watertight, as a result, high urban recharge percentage is expected from in situ groundwater users of domestic, commercial and service sectors and public institutions than industries using water recycling and irrigation farms using efficient irrigation methods. The estimation of water consumption and wastewater production was based on these assumptions.

The Hawassa City Water Supply and Sewerage Service Enterprise provided drinking water to households, commercial and service establishments, institutions and some industrial use. Of the total volume supplied, at least 20% (Foster et al., 1999b) is lost through leakage in the transmission, distribution and service connections.

This is the minimum leakage rate for an efficient water supply system. In this analysis minimum industrial and commercial demand was assumed 15% and the public demand was about 5% of the total supply. Therefore, 60% of the water supply is distributed for domestic use. As the current population of Hawassa City is estimated to be about 400,000 based on census data (CSA, 2015), the per capita water consumption per day is about 45 LPCD, which is very low, and hence many in situ water supply facilities are found throughout the city. As the total volume is insufficient, a large proportion of customers are dissatisfied with the services. Therefore, we were forced to take the maximum personal consumption up to 40% of LPCD, and this value was used to estimate the wastewater produced per capita per day.

Hawassa City has no sewerage infrastructure, so sewage and/or fecal sludge is discharged into septic tanks and pit latrines, which are not watertight. According to the feasibility study report (MWIE, 2018), less than 10% of septic tanks or pit latrines are emptied using vacuum trucks. Many service providers such as shower houses, car washes and others use soak away pits to dispose of wastewater. In estimation of volume of wastewater, the following assumption were considered

1. As the volume of water supplied for personal consumption is low consumptive use was calculated at 40% of LPCD.
2. Water supply volume for industry and commercial sectors are basic water needs, and high portion of this water is used for consumptive use. 80% of their share is estimated as consumptive use.
3. 80% of water supply to public institutions is estimated as consumptive use.
4. As the quality of in situ water supply from ground source is not potable, consumptive use of this water is very low for domestic, commercial and service providers. 20% of the volume is estimated as consumptive use.
5. Industries, agricultural farms and public institutions with in situ water supply use the water to produce products. Though there is variation in consumption between industries, public institutions and farm 60% average water consumption is estimated as consumptive use.
6. From MWIE (2018) feasibility study report about Vacuum truck wastewater transportation services in Hawassa City, 12 trucks with at most 10000 litters capacity with 6 trips per day are transporting fecal sludge to treatment plant. This service is provided for all and no clear figures from which sector they transport wastewater most. For this reason, total daily truck capacity is deducted from the total volume of wastewater generated in the City. Table 2 present wastewater estimation and transportation in daily bases for the year 2021.

Table 2. Daily wastewater estimation of Hawassa City

Source type	User Category	Volume of water delivered	Consumptive use	Wastewater generated	Transported wastewater volume	Net wastewater discharge
Public Supply	Domestic	18,000	7,200	10,800	720	17,270.24
	Industry & commercial	4,500	3,600	900		
	Public	1,500	1,200	300		
In situ	Domestic	490.1	98.02	392.08		
	Commercial & service P	1,487.2	297.44	1,189.76		
	Industries & public In.	11,021	6,612.6	4,408.4		

The daily urban recharge is 21,543.216 m^3/day. From this result the annual urban groundwater recharge was estimated at 7,863,274 m^3/yr. Currently, the active urban area of the city is expected to be 55.0737 km^2 of the total expansion area of the city. Although there is a large variation in groundwater recharge in the densely populated urban area and the rural settlement within the urban boundary, the average depth of annual urban recharge in the developed Hawassa City was estimated as 142.78 mm/yr.

Natural Groundwater Recharges Components

Natural groundwater recharge is estimated using the amount of evapotranspiration and runoff from natural precipitation in the area.

Surface Runoff using SCS-CN Method

The Hawassa watershed, where Hawassa City is located, has a bimodal rainy season with the growing season extending from March to October. November, December, January and February are the dormant season months. Antecedent moisture conditions were determined for these two seasons. The LULC with soil data of Hawassa town are presented in Table 3 and Figure 3 presents FAO & IIASA Harmonized Soil Data of Hawassa City.

Table 3. LC and site-specific Soil Data of Hawassa City for SCS CN.

Land use	WR	UR	Fle	LVx	LVh	HSf	TotalArea (Km^2)
Agriculture	0.1944	0.1161	40.3353	9.2259	9.1908	10.5363	69.5988
Forest	0.0225	0.0099	1.5264	1.1817	2.0187	0.3852	5.1444
Woody vegetation	0.054	0.4068	5.1156	0.5418	0.9531	0.7542	7.8255
Scrub land	0.0072	0.0036	0.054	0.0018		0.0162	0.0828
Grass land	0.0909	1.8648	6.3855	0.027	0.0009	0.0279	8.397
Water	0.1863	0.0036	1.1817				1.3716
Built up	0.2322	12.8943	18.4572	0.6327	0.1485	0.7884	33.1533
Bare land	0.0036	0.0432	1.5867	0.2943	0.0279	0.0657	2.0214
Swamp			1.3608			20.2383	21.5991
Masking					5.3505		5.3505
Total Area(Km^2)	0.7911	15.3423	76.0032	11.9052	17.6904	32.8122	154.5444

Based on the hydrological soil group and land cover, the specific land use CN II was selected from the Lookup (USDA, 1986) table and the weighted CN II was calculated accordingly, taking into account the area coverage of the land use. According to the AMC values of the dormant and growing seasons (Chow et al., 2002), the weighted CN II was converted to weighted CN I and CN III using (Eq.10 and 11) for dry and wet conditions respectively. Using the weighted CN values, S was calculated using (Eq.9). Three weighted curve number groups were generated, for the whole urban area, the currently active urban area of the city and the rural part of the city. The weighted CN groups are presented in Table 4.

Table 4. Weighted Curve Number different parts of the City

The Whole area		Developed City		Rural area	
CN I	56	CN I	60	CN I	52
CN II	74	CN II	78	CN II	72
CN III	87	CN III	89	CN III	86

Finally, the daily runoff was calculated considering the condition that Q has a value if P is greater than 0.05S. Four years (2017-2020) of daily rainfall data were used to determine the runoff, and finally the annual average was used to determine the water balance in Hawassa City. The average runoff depth in the whole of Hawassa City was 88.63 mm/yr, which is 7.62% of the average annual rainfall depth. However, the average runoff depth in the developed part of the city was 108.4mm/yr which is 9.3% of the average annual rainfall and in the rural area was 76.5mm/yr which is 6.5% of the average annual rainfall.

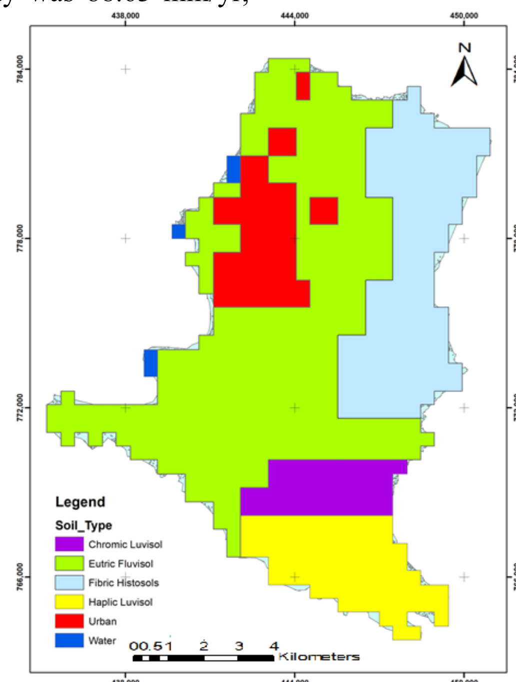

Figure 3. FAO & IIASA Harmonized Soil Data of Hawassa City

Actual Evapotranspiration Estimation

The actual evapotranspiration of a given area depends on the available precipitation. Changes in the depth of precipitation will also change evapotranspiration. With similar climate, soil and topography, higher evapotranspiration is expected in wet conditions than in dry conditions. Land Surface Temperature (LST) was derived from Landsat 8 images by the Google Earth Engine platform (Figure 4) and actual evapotranspiration calculated for different land use types (Figure 5 and Figure 6). The anchor hot (T_h) and cold (T_c) pixels temperature were 43^{0}C and 24^{0}C respectively and average ET_o was 1500 mm/year. Based on the average pixels' temperature for each land cover type ET_{fLC} and ET_{an} for each land cover type is calculated using (Eq.5) and (Eq.6). In Table (5) below is presented ET_{fLC} and ET_{an} for each land cover type.

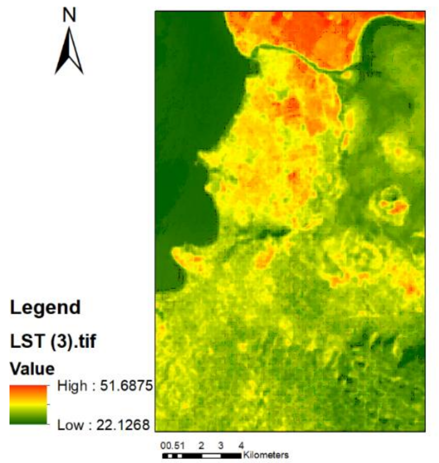

Figure 4. Land surface temperature (^{0}C) of Hawassa Area (June-November, 2020)

Table 5. Evapotranspiration fraction and Evapotranspiration for each LC

	LC	T_{av-LC} (^{0}C)	ET_{fLC}	Etan (mm/yr)
1	Built up	35.23	0.37	555.00
2	Forest	29.31	0.72	1080.79
3	Woody Vegetation	33.79	0.48	727.11
4	Scrub	36.53	0.34	510.79
5	Grass land	33.58	0.50	743.68
6	Bare land	37.42	0.29	440.53
7	Agricultural land	31.24	0.62	928.42
8	Water	26.15	0.89	1330.26
9	Wetland	29.95	0.69	1030.26

The weighted evapotranspiration for the city of Hawassa was calculated using (Eq.7). Accordingly, the average actual evapotranspiration in Hawassa city was estimated to be 841.33mm/yr and the distribution based on LC is presented in the Table 6.

Table 6. Actual Evapotranspiration of Hawassa City

	LC	ETan(mm/a)	Area(km^2)	Product(mmkm^2)
1	Built up	555.00	33.1533	18400.08
2	Forest	1080.79	5.1444	5560.01
3	Woody Vegetation	727.11	7.8255	5689.96
4	Scrub	510.79	0.0828	42.29
5	Grass land	743.68	8.397	6244.72
6	Bare land	440.53	2.0214	890.48
7	Agricultural land	928.42	69.5988	64616.99
8	Water	1330.26	1.3716	1824.59
9	Wetland	1030.26	21.5991	22252.76
Total			149.1939	125,521.88

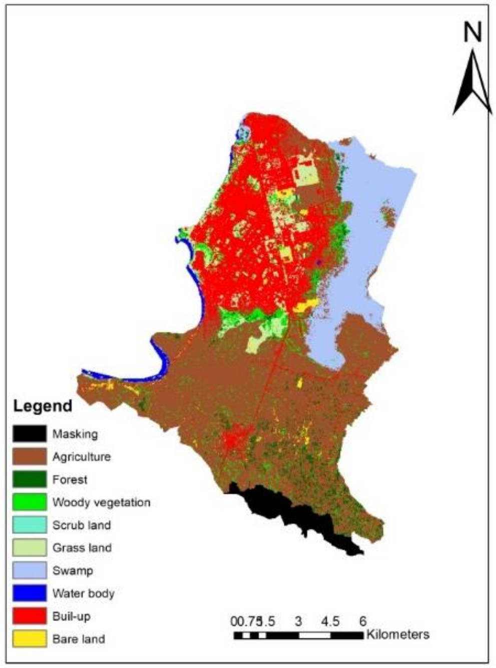

Figure 5. The 2020 LC of Hawassa City (Clipped from Wondrade, 2023)

The actual evapotranspiration of the developed city of Hawassa was estimated as 683.06 mm/yr and the distribution is presented in Table 7.

Table 7. Actual Evapotranspiration of developed part of Hawassa City

	LC	ETan(mm/a)	Area(km^2)	Product($mmkm^2$)
1	Built up	555.00	30.6351	17002.48
2	Forest	1080.79	1.0044	1085.54
3	Woody Vegetation	727.11	3.8808	2821.75
4	Scrub	510.79	0.0693	35.40
5	Grass land	743.68	7.3404	5458.94
6	Bare land	440.53	1.0674	470.22
7	Agricultural land	928.42	8.7552	8128.51
8	Water	1330.26	0.7479	994.90
9	Wetland	1030.26	1.5732	1620.81
	Total		55.0737	37,618.55

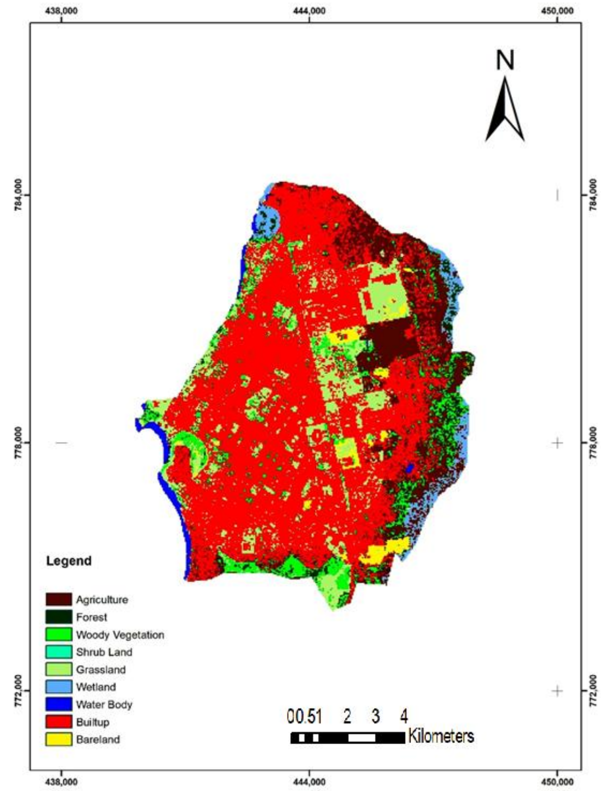

Figure 6. LC of the developed city of Hawassa modified from Wondrade (2023)

The actual evapotranspiration from undeveloped area was estimated 933.94 mm/yr. This value is greater than the value of developed area by 250.88 mm which is a lot of water. Actual evapotranspiration of the rural part of the city is presented in Table 8.

Table 8. **Actual Evapotranspiration of rural part of Hawassa City**

	LC	ETan(mm/a)	Area(km^2)	Product($mmkm^2$)
1	Built up	555.00	2.5182	1397.6
2	Forest	1080.79	4.14	4474.47
3	Woody Vegetation	727.11	3.9447	2868.21
4	Scrub	510.79	0.0135	6.90
5	Grass land	743.68	1.0566	785.78
6	Bare land	440.53	0.954	420.26
7	Agricultural land	928.42	60.8436	56488.48
8	Water	1330.26	0.6237	829.02
9	Wetland	1030.26	20.0259	20631.95
	Total		94.1202	87,902.67

From the above calculation, it is clear that the actual evapotranspiration from the undeveloped part of the city is greater than the total perimeter of Hawassa City and the developed part of the city because of the large area of wetlands and agricultural land in the undeveloped part of the city, which evaporates at a higher rate.

Natural Recharge of Hawassa City Aquifers

The natural recharge of the aquifer is calculated using (Eq.1). The variables included are precipitation, actual evapotranspiration and surface runoff.

The average rainfall in Hawassa city from Hawassa meteorological station for four years at the time of this research was 1163 mm/yr, and the calculated runoff from the entire city boundary was 88.63 mm/yr, evapotranspiration was 841.33 mm/yr and the natural recharge was 233.04 mm/yr. However, the generated runoff and evapotranspiration from the developed part of the city were 108.4 mm/yr and 683.06 mm/yr respectively, and for the rest of the city were 76.5 mm/yr and 933.94mm/yr respectively. From these values, the natural recharge for the developed part of the city and the rest of the city was 371.54 mm/yr and 152.56 mm/yr respectively. The volume of recharged water was 20.46Mm^3 and 14.36Mm^3/yr for the developed part of the city and the rest of the city respectively. The high evapotranspiration rate of the wetlands and agricultural areas is the reason for the lower recharge and volume.

Total Recharge of Hawassa City Aquifers

The total aquifer recharge in the city is the sum of the natural recharge and the urban recharge components (Eq.4). The average natural recharge component for the whole city was 233.04mm/yr and the urban recharge component was 52.7 mm/yr. The average total recharge for the whole city was 285.74 mm/yr. This value did not indicate the spatial variation of recharge in the developed and rural areas of the city. The variation in recharge was clearly seen when the recharge components in the developed city and the rural area of the city were evaluated separately. The separate analysis of recharge in the developed part of the city and in the rural areas showed that the natural recharge and urban recharge in the developed part of the city were 371.54 mm/yr and 142.78 mm/yr respectively; and the natural recharge in the rural area was 159.36mm/yr and the urban recharge component in this area was not known as there were no water supply data other than water supplied by the municipality. Though the Hawassa City Water Supply and Sewerage Service Enterprise provides drinking water to the rural Kebele settlements from separate wells, and the amount supplied was not greater than the consumptive use volume, this part was not included in this analysis.

The total recharge in the developed part of the city was 514.32 mm/yr. The natural recharge depth in the developed city is greater than the natural recharge in the rural part, which is controversial as urban areas are more impervious than rural areas. The reason for this is that the majority of LC in the rural area is wetlands and agriculture (Table 8), which has the highest evapotranspiration than urban areas (Liu et al., 2010), and the soil type in this area, is predominantly clay at the surface which constrain water infiltration. These two factors are the reason for the difference in recharge between the two areas. This is clearly seen that the evapotranspiration in the rural area is 933.94 mm/yr while in the developed city is 683.06 mm/yr. There is a difference of 250.88 mm/yr between the two evapotranspiration values.

Urban Water Balance of Developed Part of Hawassa City

This section presents the urban water balance of the city of Hawassa. It should be clear that the analysis is based on the city's rainfall and evapotranspiration being averages of different years, but the water supply from the municipal and in-situ sources are the same year values; and the analysis is based only on the available data. Inflow and outflow components are presented in Table 9.

The water inflow to the city of Hawassa includes rainwater, municipal drinking water supply, in-situ water supply from underground sources and truck water supply from the Lake for Urban greenery. The outflow component includes runoff, evapotranspiration, consumptive use volume, truck transported wastewater volume, and urban and natural recharge volume.

Table 9. Water balance of developed part of Hawassa City

Inflow	Symbol	Volume (Mm^3/yr)	Outflows	Symbols	Volume (Mm^3/yr)
Rainfall	P	173.51	Surface runoff	Q	13.223
Municipal water supply	WS	10.95	Evapotranspiration	ETa	125.52
Truck water supply	TR	0.24	Evapotranspiration G	ETg	0.24
In-situ water supply	GW	4.75	Transported Waste water	WW	0.263
			Consumptive use	CU	6.938
			Urban recharge	Uu	7.863
			Natural recharge	Un	34.77
			Waste water loss	WWl	0.630
Total		189.45			189.447

The amount of rainfall in the city was calculated based on the average rainfall depth and the total area of the city in the Lake Hawassa watershed. The mask area shown in Table 3 is part of the Gedabo watershed and the surface flow is not to Lake Hawassa. Municipal water supply and in-situ water supply volumes were calculated based on daily consumption rate and number of days per year. The truck water supply volume was calculated using the daily supply rate and an average of 200 days per year. The sum of all this was 189.45Mm^3/yr and is inflow component. This figure is not exhaustive as many in-situ water supply wells are not included due to lack of data.

Surface runoff (Q) and evapotranspiration (ET_a) volumes were calculated based on average runoff and average evapotranspiration and the area of the entire Hawassa city boundary, excluding the mask area. Evapotranspiration of greenery (ET_g) is the amount of water applied to the city's greenery during dry periods that is expected to be used as transpiration by plants or evaporate from roadside soils or asphalt roads. Consumptive use includes all domestic, industrial, institutional and commercial use from water supply and in-situ water sources. It was calculated from the daily consumptive use of all users and the number of days per year. Total aquifer recharge was calculated as the sum of natural and urban recharge per year and the total area of the urban boundary excluding the mask area. The wastewater transported to the drying bed and 10% of the generated wastewater volume that is expected to evaporate or transpire according to Lerner (2020) as WW and WWl were also included in the calculation. The sum of all these volumes was 189.447Mm^3/yr and considered as the outflow component of the water balance. Like the inflow volume the outflow volume is not exhaustive.

CONCLUSIONS AND RECOMMENDATIONS

In this study, it is observed that the groundwater recharge of the city of Hawassa is different from recharge in rural areas. Large volume of water supplied from different water sources for different water users within a limited area, and the associated leakages from the supply system and the outflow from different users as effluent are the causes of this change. In a city like Hawassa with no sewerage systems and wastewater treatment facilities, low quality water as effluent is recharging the underground. This continuous recirculation of water in the city has incremental effect of contaminating the groundwater. In Hawassa case, the urban groundwater recharge is estimated as 142.78L/m^2 area which is a lot that has a potential to contaminate the major water source for the city. Additionally, as there are water abstractions hotspots at different part of the city there is also expectation of recharge mounds at different locations based on the volume of effluents discharged in to the underground through septic tanks and/or soak away pits. This phenomenon is seen in Condominium residential areas of the city.

In water balance analysis it is clear that estimating evapotranspiration and total recharge taking the whole city boundary as one unit and separating developed part of the city from rural areas shows a great difference which is an important insight in integrated water resource planning. With increasing groundwater abstractions and implementation of the planed Sewerage systems in the developed city will bring increasing static water table depth from the surface and might abandoned shallow water wells in the future.

Therefore, to maintain water availability and increase groundwater quality in the future it is imperative to create awareness in the society about quality and quantity limitations and enforce regulatory measures with planning water resources augmentation measures. In Hawassa City, there are no established monitoring wells for water quality and groundwater level measurements, no inventory of boreholes, and no limits on the amount of water that can be abstracted from the ground. The system needs to be established urgently as it is vivid that the hot spot of high-water abstraction is located in the main water source area of the city.

CONFLICTS OF INTEREST

Authors declare that they have no conflict of interest regarding the publication of this paper.

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