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Quantifying water loss in leaky micro-dam reservoir through water balance analysis and high-resolution water level data modeling

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ABSTRACT

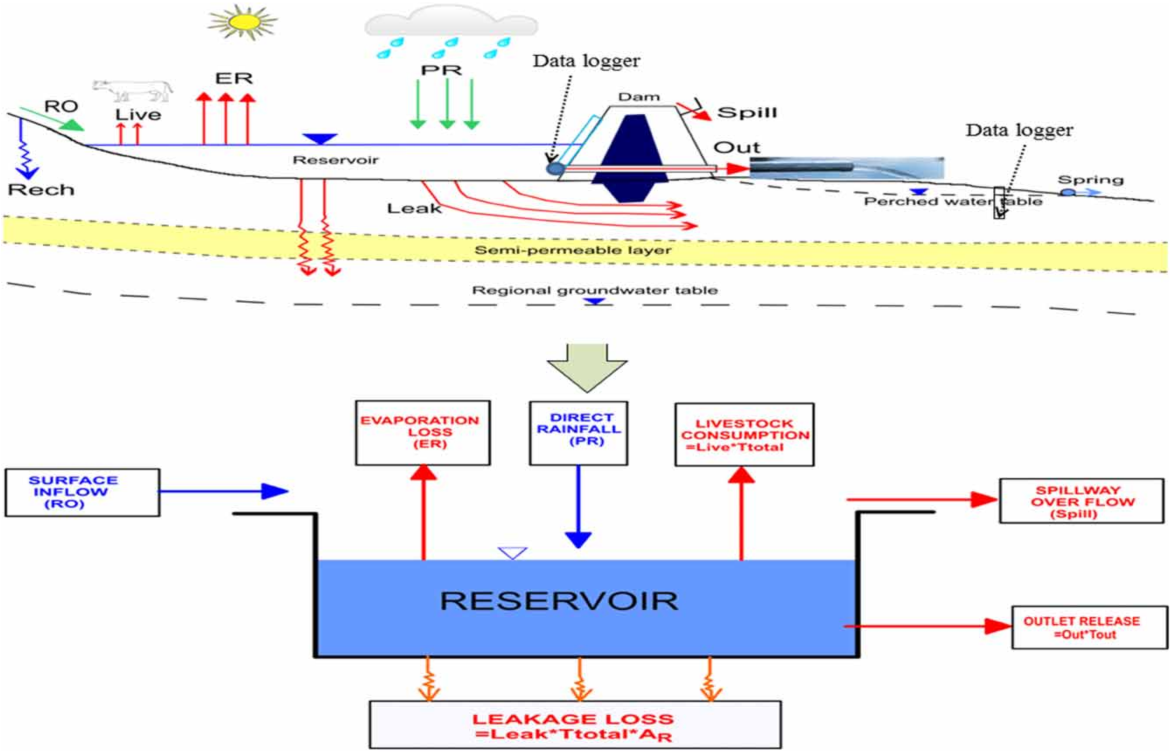
This study aimed to assess the runoff, recharge, and response of a shallow aquifer to leakage from the Arato micro-dam reservoir (MDR). The assessment was conducted using the Soil Conservation Service Curve Number (SCS-CN), soil moisture balance (SMB), and diver (automatic data logger) measurements in both the MDR and a shallow hand-dug well. Recharge was estimated using the chloride mass balance (CMB) and water table fluctuation (WTF) methods. The results revealed that the annual runoff from the catchment was 48.8 mm, which accounted for approximately 0.71 million m^3. The yearly groundwater recharge was estimated to be 104, 92.8, and 100 mm using the SMB, CMB, and WTF methods, respectively. Furthermore, the water balance model of the Arato MDR indicated a leakage rate of 13.2 mm/day. It is noteworthy that the estimated leakage exceeded the seepage initially anticipated during the project's design phase (9,965 m^3/year). This research project highlights the significance of utilizing local climatic and physical data from the specific watershed under investigation when planning reservoirs and other water resources. It also underscores the importance of conducting thorough site investigations to accurately quantify hydraulic conductivity for leakage estimation purposes.

Key words: curve number method, diver data, Ethiopia, groundwater recharge, Tigray

HIGHLIGHTS

- Integrated approach used.
- Technology (pressure transducer/data loggers) for high-resolution data used.
- Interaction between leakage of the reservoir and shallow aquifer evaluated.
- Employed in the data-scarce area.
- Local meteorological data collected and used for analysis.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is an essential resource for sustaining life and agricultural production (Khan & Hanjra 2008). Understanding the various components of the water balance is crucial for effective water resource management. The partitioning of precipitation into different variables of the water balance is important for sustainable water quality and quantity management (Sophocleous 1991; De Vries & Simmers 2002; Singh 2014), as well as for the planning and design of water harvesting (Biazin *et al.* 2012) and flood control structures. It is particularly significant in arid and semi-arid regions where the impact of climate change is significant.

Hydrological phenomena, such as runoff, flow regime, sediment transport, and surface water–groundwater interaction, play a significant role in land degradation. On the other hand, hydrological interventions can aid in the restoration of catchments and the planning of water harvesting schemes. Understanding the surface water–groundwater interactions of an area is crucial for ecological and water resource development and management (Ferone & Devito 2004; Jolly *et al.* 2008).

Climatic factors, especially precipitation, are particularly important for the recharge of shallow aquifers. The hydrological cycle, land degradation and management, and environmental sustainability are all interconnected (Khan & Hanjra 2008).

Leakage-related problems in reservoirs have been observed worldwide. For example, the McMilan Reservoir in the USA dried up after 12 years of operation (Pearson 1999). In the UK, approximately 30% of embankment dams constructed between 1854 and 1960 experienced incidents primarily due to leakage. Additionally, nearly 173 reservoirs in the UK have been abandoned due to various types of failures (Tedd *et al.* 2000). A compilation of 900 dam failure cases from around the world showed that the majority of failures were on earth dams and occurred within the first 5 years of service. Leakage and piping were the main causes of dam failures (Zhang *et al.* 2007).

The livelihoods of people in Ethiopia depend heavily on land resources for food and other necessities, with the majority of the population engaged in agricultural activities (Central Statistics Authority CSA 2008; Adimassu & Haile 2011; Adimassu *et al.* 2014). However, water availability is a limiting factor for agricultural and economic activities in many parts of the country due to low and erratic rainfall patterns. Rain-fed agriculture is common in Ethiopia, and food self-sufficiency is still in its early stages. To address this issue, the government of Ethiopia is constructing various water harvesting structures (WHSs), including micro-dam reservoirs (MDRs) to store runoff water for domestic and irrigation purposes. However, these initiatives have faced challenges related to leakage, siltation, insufficient runoff, and inefficient water management (Desta 2005; Yazew 2005; Haregeweyn *et al.* 2006).

To address the existing problems and develop a sustainable strategy, it is crucial to gain a comprehensive understanding of the rainfall–runoff–recharge system in the area. The previous research has utilized various approaches, including engineering geological, geophysical, and hydro-geochemical methods, to assess the leakage phenomenon. Detailed studies involving geological, geophysical, and hydro-geochemical analyses have been conducted at selected MDRs, including the Arato MDR (Berhane *et al.* 2013, 2016). The Arato MDR, one of the 92 MDRs in Tigray, has been significantly affected by leakage problems since its construction in 1997. The results of previous studies have emphasized a significant hydraulic connection between the reservoir and the leakage zones, particularly within a limestone–shale–marl intercalated rock unit (Berhane *et al.* 2013, 2016). Based on the findings, it has been determined that the reservoir is experiencing leakage through the subsurface foundation and left flank materials.

In light of this, the objective of this paper is to build upon the previous work by employing a water balance approach and utilizing high-resolution water level sensors. The paper aims to evaluate reservoir leakage by analyzing the water balance and recharge–runoff processes, while also comparing the results with previous research and different techniques. By doing so, it aims to contribute to a better understanding of the leakage issues and provide insights for developing effective strategies to address them.

2. GEOLOGICAL AND HYDROGEOLOGICAL CONTEXT

The geology of northern Ethiopia can be classified based on the stratigraphic sequence. Starting from the youngest to the oldest, the geological formations are as follows: Flood Basalt (Paleo-Neogene/Quaternary Volcanics); Amba Aradam (Upper Sandstone); Agula Shale; Antalo Limestone; Adigrat Sandstone (Lower Sandstone); Enticho Sandstone and Edaga Arbi Tillite and Upper Complex Metamorphic (Basement) rocks. In addition to these formations, there are also Quaternary soil deposits found in depressions and on flat landforms.

The occurrence of groundwater in the Mekelle Outlier region is closely associated with fracturing and joints (faults) as well as the impact of dolerite intrusion on the surrounding rock. The Mekelle Outlier is a nearly circular area spanning approximately 8,000 km^2, where the Mesozoic sedimentary succession has been preserved from erosion. Detailed geological information about the Mekelle area, including the Outlier and its stratigraphy, can be found in the works of Beyth (1972), Levitte (1970), and Gebreyohannes (2009).

Girmay *et al.* (2015) identified three groundwater flow systems in the study area: shallow/local, intermediate, and deep/semi-regional. The shallow groundwater flow is concentrated in the highland plateau areas, particularly in the Agula Shale and dolerite formations, which exhibit characteristics of shallow and localized groundwater flow systems. For detailed information about the geological and hydrogeological conditions of the site, including maps and sections, refer to the studies conducted by Berhane *et al.* (2013, 2016).

The study area is overlain by Mesozoic sedimentary rocks and Paleo-Pliocene Volcanics. The mineralogical composition of limestone and dolerite has been summarized based on thin-section analysis conducted at the Geological Survey of Ethiopia (Addis Ababa) as part of the present study (Table 1).

3. MATERIALS AND METHODS

3.1. Description of the study area

The study area, Arato MDR, is situated approximately 25 km east of Mekelle City (see Figure 1(a) and (b)). Arato MDR was constructed with a dam height of 20 m and a gross reservoir capacity of 2.59×10^6 m^3, specifically for the purpose of irrigation (Table 2). The catchment area that supplies runoff to Arato MDR covers an area of 20.7 km^2. It is worth noting that Arato MDR exhibits a common issue seen in many irrigation schemes, which is leakage. The location of Arato MDR and its surroundings are depicted in Figure 1(a) and 1(b). The topographic elevation in the study area ranges from 2,400 to 2,560 m above sea level (a.s.l).

The average annual rainfall in the area, based on data from the Mekelle meteorological station, slightly exceeds 600 mm, with the highest rainfall occurring in July and August (Figure 1(c)). The majority of the precipitation, around 70–80% annually, falls during the 'Kiremt' (summer) season, which spans from June to September. In

Table 1 | Summary of mineral compositions of limestone and dolerite units from Arato MDR (numbers indicate sample code)

Mineral (%)	Limestone 1	Limestone 2	Limestone 3	Dolerite 1	Dolerite 2	Dolerite 3
Calcite	92	70	71			
Plagioclase	5	2		39	43	37
Clay		25				
Opaque (Fe-oxide)	3	3	6	12	15	15
Fossil			20			
Pyroxene				32	32	33
Biotite				17	10	10
Amphibole						3
Chlorite						2
Rock name	Limestone	Argillaceous limestone	Fossiliferous limestone	Dolerite porphyry	Dolerite porphyry	Dolerite porphyry

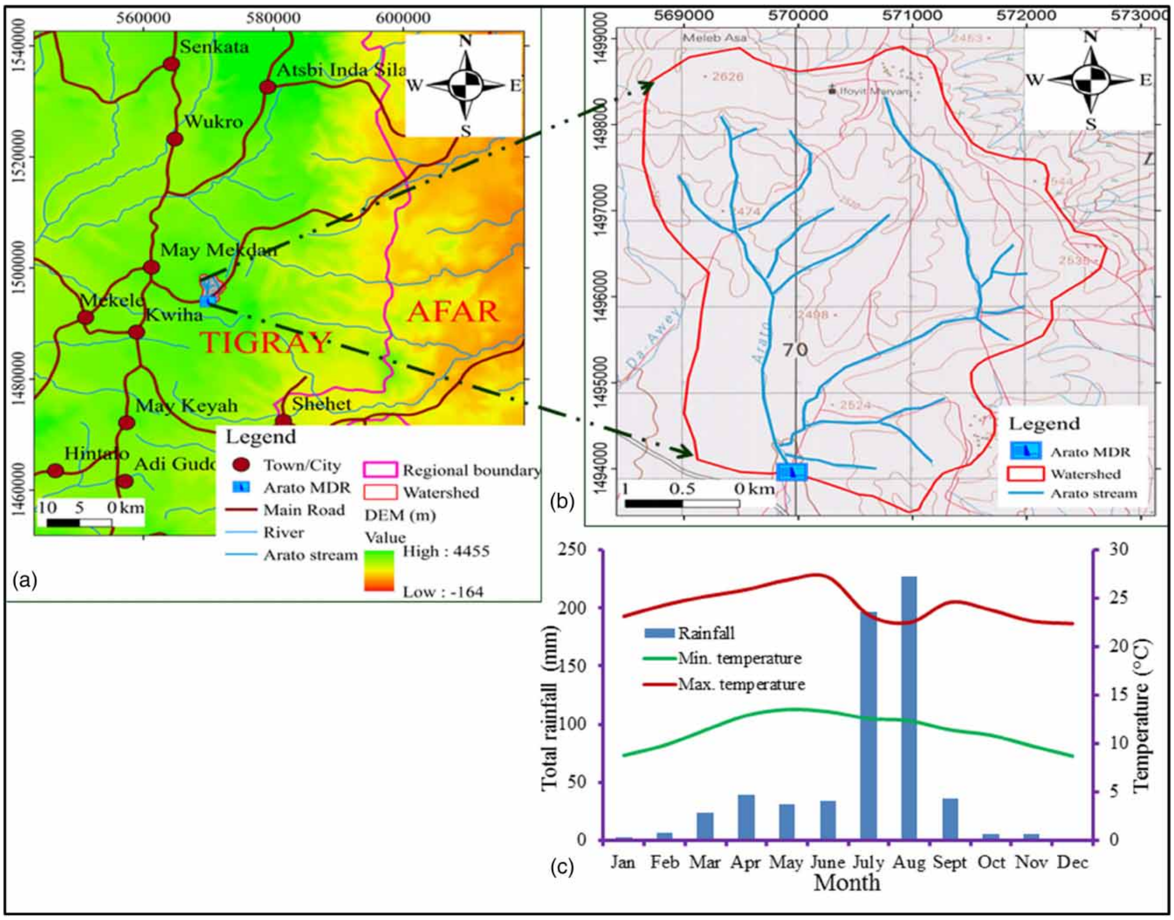


Figure 1 | (a,b) Location map of Arato MDR (Adindan UTM Zone 37 N coordinate system). *Note:* Mekelle weather station in (a), and (c) average monthly rainfall, and minimum and maximum temperature from Mekelle station (Ethiopian Meteorological Agency data 1960–2006).

certain years, rainfall may commence later, in July, and the months of March, April, May, and June experience negligible rainfall.

The mean minimum temperature varies from approximately 9 °C in December to 13 °C in May and June, while the mean maximum temperature ranges from 22 °C in December to around 27 °C in June.

Table 2 | Characteristics of the dam–reservoir utilizing for the research

S.No.	Description of the dam–reservoir	Values: Designed	Values: Actual	Remark
1	Dam height	20 m	20 m	
2	Reservoir capacity	2.59 Mm^3	0.71 Mm^3	No sufficient inflow
3	Command (area for irrigation)	120 ha	27 ha	
4	Catchment area	20.7 km^2		
5	Crest length (length)	447 m		
6	Year of construction	1997		
7	Main use	Irrigation and livestock		
8	Main lithology	Shale, limestone, dolerite		

3.2. Methods

3.2.1. Establishment of meteorological station

Due to the considerable distance (approximately 20 km) between the existing meteorological stations and the study site, a new meteorological station was established specifically for this research on 18 July 2014. The station was equipped with a manual rain gauge and a minimum–maximum thermometer. Rainfall and minimum–maximum temperature measurements were recorded on a daily basis from 19 July 2014, to 16 January 2015, spanning a period of 182 days (Figure 2).

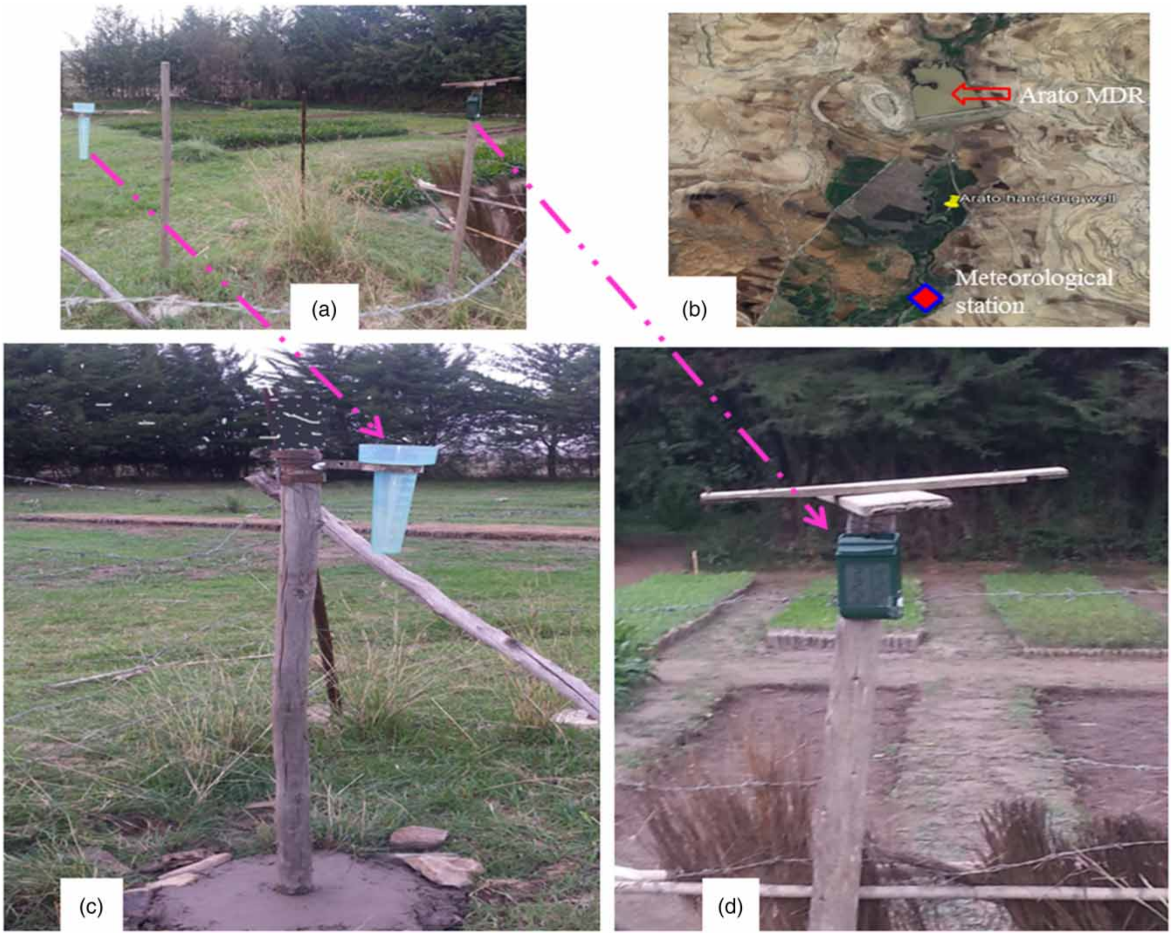


Figure 2 | Details of the Arato MDR and the established meteorological station (569,991.1 mE, 1,492,953.79 mN, 2,396 m a.s.l.) for this research at the Arato site. (a) Field photo illustrating rain gauge and Min–Max. Thermometer, (b) Google Earth Pro map (accessed on 2/12/2023) showing Arato MDR, and (c,d) details of field photograph of (a). Field photographs by the first author.

3.2.2. Installation of water level sensors

High-resolution water level sensors, known as pressure transducers, manufactured by Schlumberger Water Services (Canada) under the name DIVER CE©, were installed in two locations: the reservoir and a shallow hand-dug well (SHDW) adjacent to the reservoir on the downstream side (refer to Figure 3). The water level sensor in the reservoir has a measurement range of 20 m, indicating the height of the water column above the sensor tip. On the other hand, the sensor in the SHDW has a range of 10 m. Measurements were programed to be taken at 30-min intervals, capturing the pressure exerted by the water column in addition to the atmospheric pressure.

To protect the pressure transducers from damage, they were installed inside a pipe. Since the MDR lacks a tower to vertically lower the sensor, a pipe was laid along the upstream slope of the dam to house the sensor. During installation, the proper functioning of the sensor was tested to ensure accurate readings (see Figure 3(a)). The SHDW is an open, circular-shaped well with a diameter of 4 m, a depth of approximately 6 m, and composed of alluvial deposits (including silt, clay, and some sandy materials toward the bottom).

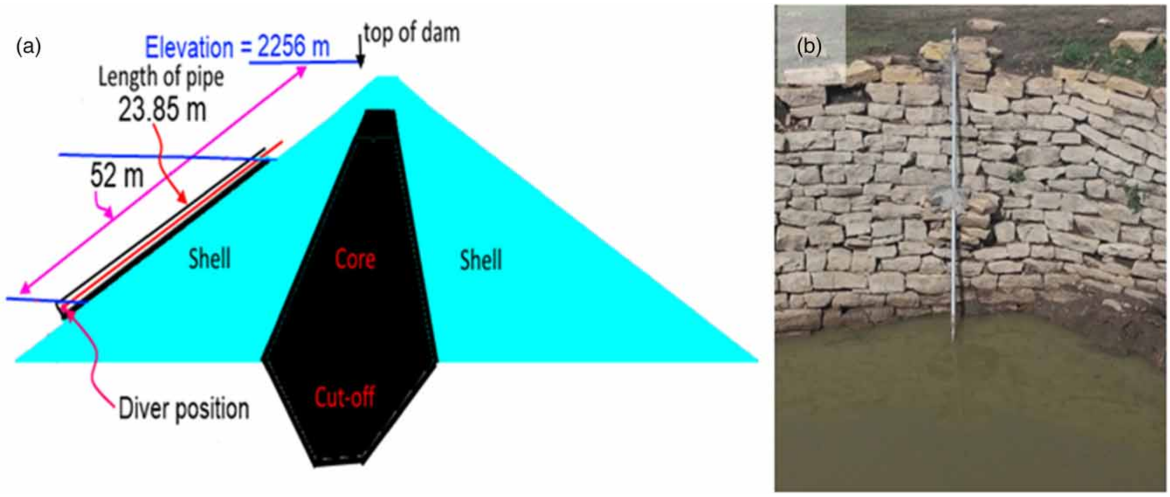


Figure 3 | High-resolution water level sensor/logger installation: (a) installation details of the sensor in MDR, and (b) installation of a sensor in SHDW (inside the steel pipe).

The water level sensor measures the total pressure, from which the piezometric head can be determined after compensating for atmospheric pressure. To compensate for atmospheric pressure, a barometric pressure transducer was also installed at the meteorological station, solely recording atmospheric pressure data.

3.2.3. Runoff

To estimate the runoff of the area, the Soil Conservation Service Curve Number (SCS-CN) method (USDA-SCS 1985) was utilized. This method relies on actual meteorological records obtained at the site. CN is a dimensionless parameter indicating the runoff response characteristic of a watershed or drainage basin. It is derived from established tables based on the characteristics of the site. The major factors that determine CN are (a) the hydrologic soil group (HSG), (b) land cover type, (c) catchment treatment, (d) hydrologic conditions, and (e) runoff condition. A weighted average CN was determined for the catchment based on factors such as land use, hydrologic conditions, and HSG. The land use map and soil condition/soil group of the catchment were established through field observations, Google Earth, aerial photographs, and existing laboratory tests.

The direct surface runoff, as calculated by the SCS-CN method, is expressed by the following equation:

$$\mathrm{RO} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{1}$$

where RO represents the direct surface runoff, P is the precipitation, and S is the potential maximum retention after runoff begins (Jeon *et al.* 2014), both measured in millimeters (mm). The value of S is estimated from the dimensionless CN as follows:

$$S = 25.4\left(\frac{1,000}{\mathrm{CN}} - 10\right) \tag{2}$$

To estimate the catchment yield, the following equation was used (Flayin *et al.* 2022):

$$\Delta V_{\mathrm{R}} = \mathrm{RO} \times A_{\mathrm{c}} = \mathrm{RC} \times P \times A_{\mathrm{c}} \tag{3}$$

where ΔV_{R} represents the volume of water generated, RC is the runoff coefficient, A_{C} is the catchment area, and P is the precipitation.

3.2.4. Reference evapotranspiration ($\mathrm{ET_o}$)

Reference evapotranspiration ($\mathrm{ET_o}$) is a crucial component in water balance models and is influenced by various factors, including weather, crop characteristics, and environmental factors. In this study, the Food and Agriculture Organization (FAO) Penman–Monteith equation (Allen *et al.* 1998) was employed to estimate $\mathrm{ET_o}$. The equation is expressed as follows:

$$\mathrm{ET_o} = \frac{0.408\Delta(R_n - G) + \gamma((900)/T + 273)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

where $\mathrm{ET_o}$ represents the reference evapotranspiration in millimeters per day (mm/day), R_{n} is the net radiation at the crop surface in megajoules per square meter per day (MJ/m^2/day), G is the solar heat density in MJ/m^2/day, γ is the psychrometric constant in kilopascals per degree Celsius (kPa/°C), u_2 is the wind speed at 2 m above the ground in meters per second (m/s), e_{s} is the saturation vapor pressure in kilopascals (kPa), e_{a} is the actual vapor pressure in kPa, $e_{\mathrm{s}} - e_{\mathrm{a}}$ is the saturation vapor pressure deficit in kPa, and Δ is the slope of the saturation vapor pressure curve in kPa/°C.

The estimation of reference evapotranspiration was conducted on a daily basis for a period of 182 days using the FAO ETo calculator/program (FAO 2009). In addition to the parameters recorded at the local station, default values based on the geographic location were utilized.

3.2.5. Groundwater recharge (Rech)

The estimation of recharge for the entire catchment or water budgeting was carried out using the soil moisture balance (SMB) method, as described by Thornthwaite & Mather (1957). The equation representing the SMB method is as follows:

$$P = \mathrm{AET} + \mathrm{RO} + \Delta\mathrm{SW} + \mathrm{Rech} \tag{5}$$

where P represents precipitation, AET is the actual evapotranspiration, ΔSW is the change in soil water over a time step, and Rech is the groundwater recharge.

The SMB model is a lumped model that tracks soil water over time, treating the entire watershed as a single unit. Water is stored in the soil reservoir until the soil water content (SW) exceeds the field capacity, at which point recharge occurs. The soil water balance requires monitoring the accumulated potential water loss (APWL) and the amount of water in the soil (SW). The model can be applied at daily, weekly, or monthly time steps. In this study, a daily time step was used for a duration of 182 days.

Calculations to determine SW and APWL were performed for each day using daily precipitation (P), reference evapotranspiration ($\mathrm{ET_o}$), and runoff (RO) in an Excel sheet. Detailed procedures can be found in Steenhuis & Van Der Molen (1986).

The model requires local rainfall data, $\mathrm{ET_o}$, plant available water (PAW) (the difference between volumetric water content at field capacity and permanent wilting point), and runoff (RO) as inputs. PAW was estimated based on vegetation cover and soil texture using the method proposed by Thornthwaite & Mather (1957). For this study, a PAW value of 200 mm was used, considering moderate-rooted cereals and clay loam as the dominant cover and soil type, respectively.

Additionally, groundwater recharge was estimated using the environmental tracer – chloride mass balance (CMB) and water table fluctuation (WTF) methods for comparison.

The CMB method compares the total chloride deposition at the surface with the chloride concentrations reaching the groundwater, assuming chloride to be a conservative ion. Recharge (Rech) is estimated as follows (Marei *et al.* 2010; Buana *et al.* 2023):

$$\text{Rech} = \frac{P_{\text{eff}}\text{Cl}_{\text{P}}}{\text{Cl}_{\text{gw}}} \tag{6}$$

where P_{eff} represents effective precipitation in millimeters (mm), Cl_{P} is the chloride concentration of precipitation (samples were directly collected from rain), including dry deposition in parts per million (ppm), and Cl_{gw} is the constant chloride concentration of groundwater in ppm.

Effective precipitation refers to the amount of precipitation that is actually added and stored in the soil after runoff is removed. Rainwater and groundwater samples were collected from the area in 2014, directly from raindrops and from SHDW where the water level sensor was installed, respectively. All water samples were analyzed at the Laboratory for Applied Geology and Hydrogeology of Ghent University, Belgium.

The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water reaching the water table. Groundwater recharge (Rech) is calculated as follows (Healy & Cook 2002; Addisie 2022):

$$\text{Rech} = S_{\text{y}}\frac{dh}{dt} = S_{\text{y}}\frac{\Delta h}{\Delta t} \tag{7}$$

where S_{y} represents the specific yield, h is the water table height, and t is the time.

The WTF method is most suitable for shallow water tables that exhibit sharp water level rises and declines. The study site has a typical shallow aquifer that experiences water level rises during the wet season due to direct natural groundwater recharge and leakage from the MDR.

3.2.6. Water balance model for Arato MDR

A conceptual water balance model was created to accurately reflect the specific conditions of the Arato MDR area. This model takes into account available data and existing knowledge of the region. The water balance model is visually represented in Figure 4.

The model considers various factors over a specific time period, such as a month or hydrological year. These factors include inflows in the form of runoff (RO) from the watershed and direct rainfall (PR) on the reservoir's surface. Outflows are accounted for through evaporation from the water surface (ER), water consumed by livestock (Live), water released through the spillway (Spill) and outlet (Out), as well as losses due to leakage (Leak) (refer to Figure 4).

In accordance with the principle of conservation of mass or volume, the change in water volume within the reservoir can be calculated by subtracting the output volume from the input volume (Rodríguez-Huerta *et al.* 2020). For Arato MDR, this simplified conservation of mass or volume can be further expanded.

The water balance model was applied separately for dry and wet periods to estimate leakage (Leak) and runoff (RO), respectively. It is important to note that the determination of runoff (RO) can be done independently using this model, without relying on the results obtained from the CN method.

$$\Delta V_{\text{R}} = [\text{RO} + (\text{PR} \times A_{\text{R}})] - [(\text{ER}) + (\text{Live} \times T_{\text{total}}) + \text{Spill} + (\text{Out} \times T_{\text{out}}) + (\text{Leak} \times A_{\text{R}} \times T_{\text{total}})] \tag{8}$$

The change in volume within the reservoir can be represented by examining the fluctuations in the water level of the reservoir.

$$\Delta V_{\text{R}} = V_{\text{Rf}} - V_{\text{Ri}} = \Delta\text{WL}_{\text{R}} \times A_{\text{R}} \tag{9}$$

$$A_{\text{R}} = \frac{A_{\text{Ri}} + A_{\text{Rf}}}{2} \tag{10}$$

where ΔV_{R} is the change in the reservoir volume (m^3); $\Delta\text{WL}_{\text{R}}$ is the reservoir water level variation (m); A_{R} is the average reservoir area (m^2); V_{Ri} is the reservoir volume at the initial time (m^3); V_{Rf} is the reservoir volume at the final time (m^3); A_{R} is the average reservoir area (m^2); A_{Ri} is the reservoir area at initial time (m^2); A_{Rf} is the

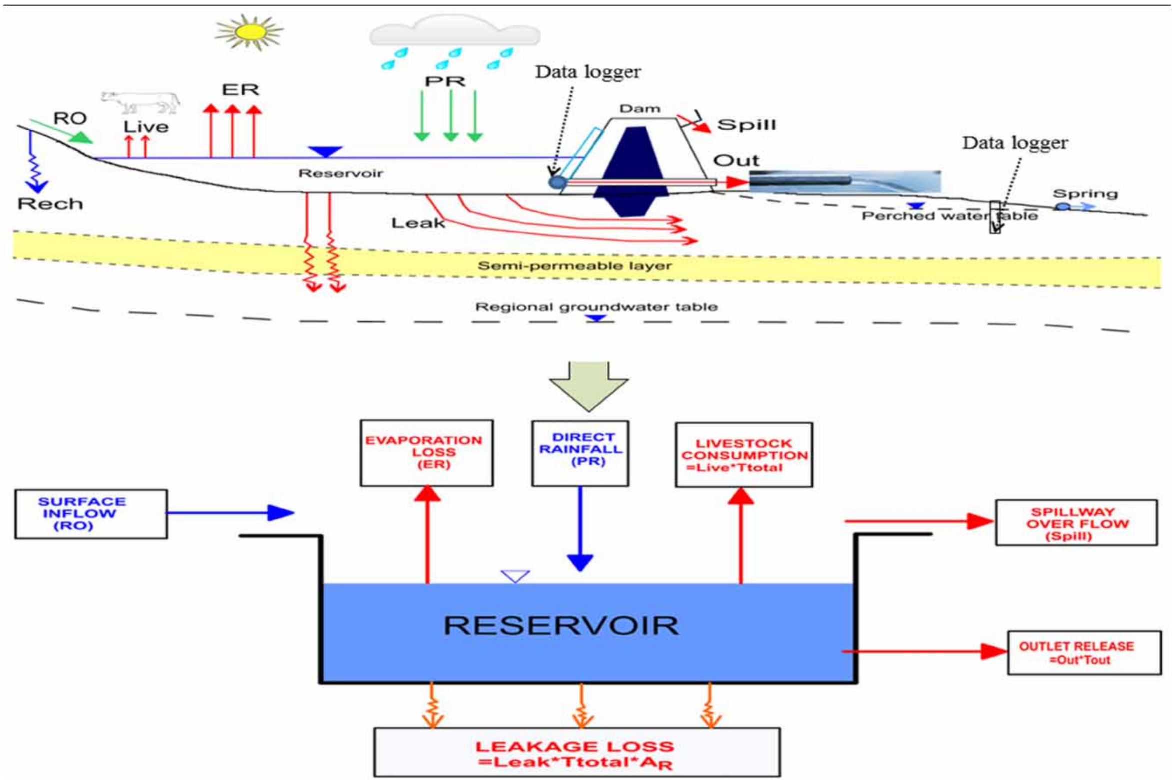


Figure 4 | Schematic representation of water balance components of Arato MDR. The schematic location of the data loggers in the reservoir and SHDW are indicated.

reservoir area at final time (m^2); PR is the direct rainfall on the reservoir (m); RO is the runoff (m^3); RI is the direct rainfall over the reservoir surface (m^3); ER is the evaporation loss from reservoir (m^3); ET_o is the reference evapotranspiration (m); Rech is the direct recharge; T_{total} is the number of days; Out is the daily reservoir loss through outlet (m^3/day); T_{out} is the outlet operation time (days); Live is the daily reservoir loss due to livestock consumption (m^3/day); Leak $\times A_R \times T_{total}$ is the reservoir loss due to leakage (m^3); Spill is the spillway overflow (m^3).

To calculate the reservoir water loss caused by evaporation from the surface of the reservoir, potential evapotranspiration is used due to the absence of pan evaporation data at or near the study site. It is important to note that using data from pans located far from the water body under investigation can lead to significant errors, as suggested by Winter (1981).

To convert reference evapotranspiration rates to an open water surface, Penman (1948) provides factors ranging from 1.25 to 1.67. Additionally, Doorenbos & Pruitt (1984) present empirical factors, also known as crop coefficients, for converting reference evapotranspiration to open water body evaporation. For dry environments with strong wind (comparable to the present study site), an empirical factor of 1.2 is suggested for all types of water bodies.

In a study conducted in northern Ethiopia by Teka *et al.* (2013), it was assumed that open water evaporation is 10% (factor of 1.1) higher than the reference evapotranspiration (ET_o). Abdurahman (2009), who conducted research near the study site, used a factor of 1.33 to convert potential evapotranspiration into reservoir evaporation. For the present study, a factor of 1.33, as adopted by Abdurahman (2009), is used to convert reference evapotranspiration into reservoir water evaporation (Equation (11)).

$$\mathrm{ER} = 1.33 \times \mathrm{ETo} \times A_R \tag{11}$$

Moreover, the inflow due to direct rainfall on the surface of the reservoir water body was estimated as:

$$\mathrm{RI} = \mathrm{PR} \times A_R \tag{12}$$

where A_R is the average reservoir area (m^2); PR is the direct rainfall over the reservoir (m); RI is the direct rainfall or input over the reservoir surface (m^3); ER is the evaporation loss from reservoir (m^3); ET_o is the reference evapotranspiration (m).

Indeed, calibration is necessary when employing the water balance model approach in isolation, without supplementing it with other methods. In the present scenario, it utilized the CMB and WTF methods to cross-validate the outcomes of the water balance model. Additionally, the model was executed using the measured volume of water stored in the Arato Reservoir. Consequently, the reliability of the Arato MDR water balance model is already presumed, as it has been verified through independent methods and recorded data at the reservoir.

The various software applications utilized for constructing, drawing figures, and analyzing models were ArcMap 10.4 (ArcGIS), Microsoft Excel 2010, GrapherTM 8, Surfer 10, and Microsoft Power Point 2010.

4. RESULTS

4.1. Water level dynamics from data loggers

Figure 5 illustrates the high-resolution water level measurements in the MDR and SHDW, in relation to daily rainfall. It is worth noting that the increase in both reservoir water level and groundwater level in the SHDW resumed following the onset of rainfall on 20 July 2014. The observations of water levels began at the start of the rainy season, as there was a delay in rainfall in 2014, which lasted for less than 3 months. Given the rainfall pattern of the region, it is reasonable to assume that the entire wet period occurred within the 182 days of observation. During the remaining part of the hydrological year, it can be assumed that runoff and groundwater recharge were negligible.

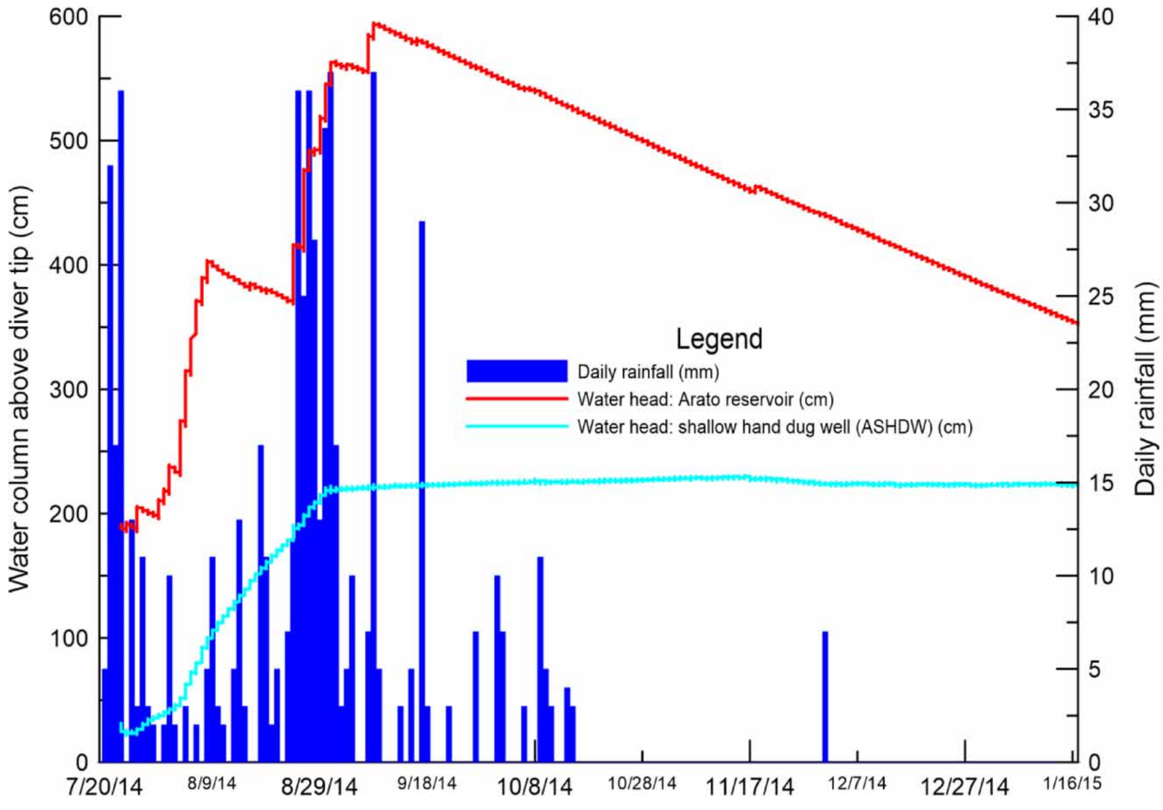


Figure 5 | High-resolution water level data from the reservoir and the SHDW, and rainfall. Data from loggers are compensated for atmospheric pressure.

Throughout the 182-day period, the total rainfall amounted to approximately 633 mm, with only 55 days experiencing rainfall. The individual rainfall totals ranged from 2 to 37 mm. The reservoir and groundwater levels rose to a maximum of about 6 and 2 m, respectively. However, the rise in groundwater level in the SHDW was incomplete due to the well starting to overflow caused by leakage and the presence of a confining clay layer. During the period of measurable rise in the SHDW (before overflowing), a cumulative rainfall of 446 mm was recorded, while for the reservoir, it was about 530 mm. The WTF method was applied only during the period when the well did not overflow. The CMB and SMB methods were used to account for the discrepancy caused by the well overflowing.

The hydraulic gradient between the reservoir and the SHDW, where the water level sensor was located, was estimated to be approximately 0.043. This estimation was based on the elevation of the reservoir and groundwater levels, which were measured at 2,424 and 2,398 m, respectively, and a horizontal distance of about 600 m.

4.2. Runoff

At the study site, there was no device specifically designed to measure runoff. Therefore, the estimation of surface runoff was carried out using the SCS-CN method. A weighted CN was used for the entire watershed based on the land use and soil type characteristics.

The catchment area, as shown in Figure 6, is primarily comprised of agricultural land with some marginal areas where grass grows during the rainy season. Analysis of soil samples collected from the area revealed a range of grain size distributions, including loamy sand, loam, and clay, as presented in Table 3. It is important to note that

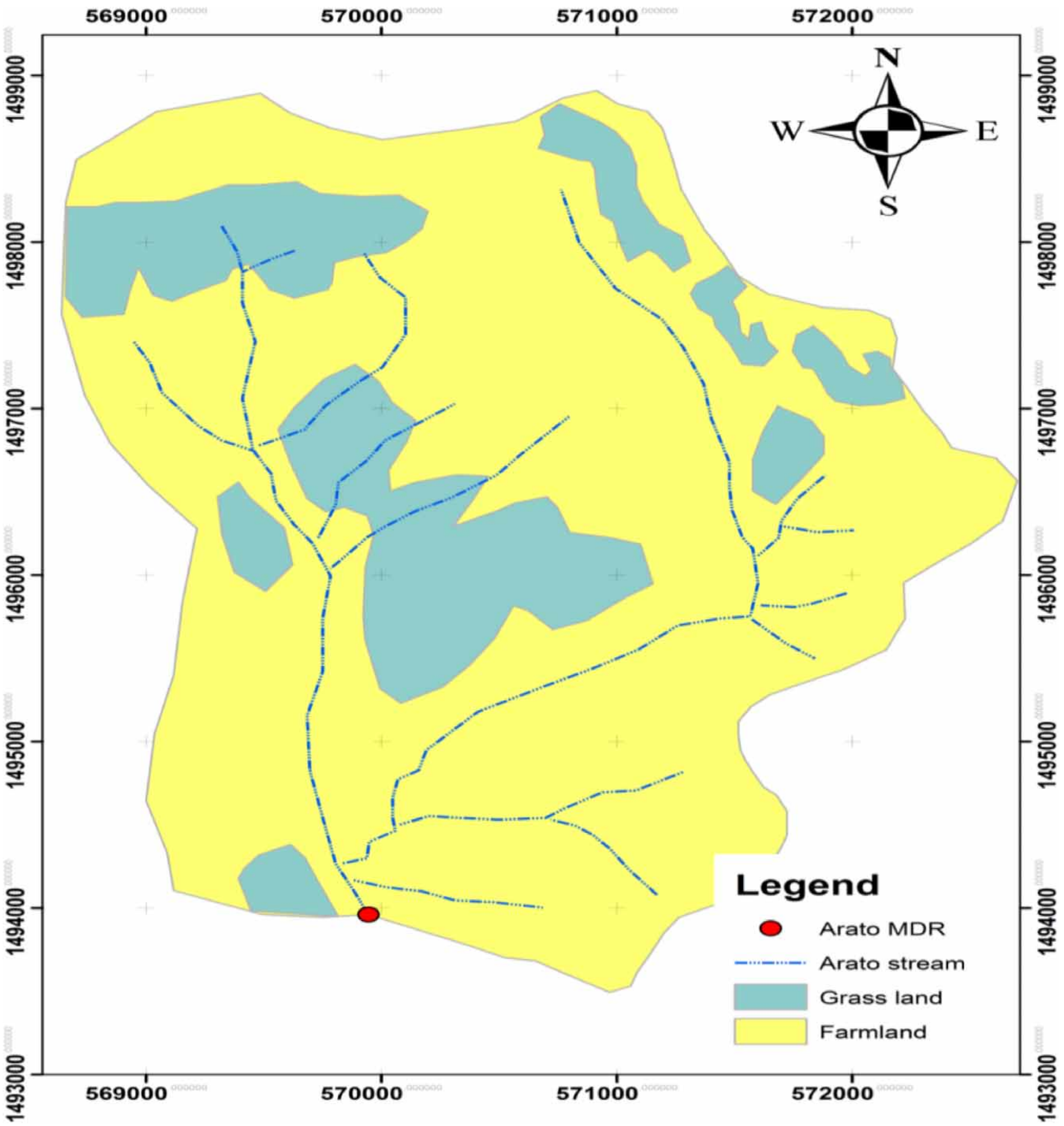


Figure 6 | Simplified land use map of Arato watershed. The location of the three soil samples coincides with the location of the MDR.

Table 3 | Grain size distribution of soil samples taken from the dam site (Hagos 1995)

S. No	Sample location	Sand fraction	Silt fraction	Clay fraction (%)	LL	PL	PI	USDA soil classification	Hydraulic conductivity (cm/s)
1	DDA1[a]	44	40	16	44	21	23	Loam	Not available
2	DDA2[a]	88	9	3	NP	NP	NP	Loamy sand	Not available
3	DDA3[a]	3	7	90	65	27	38	Clay	Not available
4	Chichat UP[b]	6	12	82	63.7	30.4	33.3	Clay	1.0×10^{-7}

Sample locations are from farm land at the dam axis (LL, liquid limit; PL, plastic limit, PI, plasticity index; NP, non-plastic).
[a]Data or samples taken from Arato dam site.
[b]Data or sample taken outside the catchment area but close to the study site.

the two soil samples mentioned earlier were obtained from small sections of the catchment, specifically the dam site, and were not collected for the purpose of this study. Their inclusion here is merely to demonstrate the variations in soil texture across the area. Based on field observations and previous studies by Gebreyohannes (2009) and Kassa (2011), it was determined that the dominant or representative soil type for the watershed is clay loam. The presence of shale in the catchment area contributes to the formation of clayey soils.

To estimate the CN, the specific characteristics of the clay loam soil were taken into account; including its poor to fair hydraulic condition and its classification as HSG C, as outlined in Table 3. In addition, the farming practices in the area involve plowing and treating the plots in accordance with the topography, following contour lines. This contoured treatment or practice was considered for the entire area. Minor terraces were also observed in the grassland areas. The CN value was calculated by weighting the surface area of different land uses and resulted in a value of 79.6 for the entire watershed, as shown in Table 4.

Table 4 | Weighted CN for the whole Arato catchment

Land use	Area (sq.km)	Area ratio	Hydraulic condition	Hydrologic soil group	CN	Weighted CN	Sum weighted CN
Grass land/bush	2.87	0.2	Fair	C	70	14	79.6
Farm land/small grain	11.58	0.8	Poor	C	82	65.6	

Considering the weighted CN for the entire catchment, along with a corresponding potential maximum retention (S) value of 65.1, the runoff generated from the catchment over a period of 182 days amounted to 48.8 mm. This runoff volume represents approximately 7.7% of the total rainfall received during that period, which was 633 mm. This can be expressed as an RC of 0.077. It is worth noting that out of the 182 days, only 13 days experienced rainfall that resulted in runoff, with runoff amounts ranging from 0.2 to 6.5 mm. The remaining 55 rainy days had precipitation levels ranging from 2 to 37 mm, but did not generate any significant runoff. To provide a broader context, Table 5 presents various study findings from Tigray and other regions of Ethiopia for comparison.

4.3. Groundwater recharge (Rech)

Groundwater recharge occurs when there is excess rainfall and the soil moisture reaches its field capacity. The estimation of recharge using the SMB model is summarized in Table 6 and Figure 7. The recharge during the period was 104 mm, which accounted for approximately 16% of the total rainfall. Recharge took place only on seven specific days (4 days in August and 3 days in September). The maximum daily recharge was 25.6 mm, while the minimum was 5.3 mm. The total potential evapotranspiration (ET_o) and actual evapotranspiration (AET) for the 182-day period were approximately 888.5 and 509 mm, respectively.

Moreover, recharge was estimated using CMB. The chloride concentration in rainwater was around 0.98 mg/l, which is comparable to previous studies in the Mekelle area (0.8 mg/l) (Kahsay 2008) and in Mugher (0.88 mg/l), Jema (0.97 mg/l), and Upper Awash (0.84 mg/l) areas (Berehanu *et al.* 2017). However, it is lower than the weighted average reported for Mendae Plain (Tigray, Ethiopia) (2.6 mg/l) (Walraevens *et al.*

Table 5 | Estimated runoff and recharge per year in different parts of Ethiopia compiled from different sources expressed as percentage of rainfall in parentheses

Source	Area	Runoff (mm)	Recharge (mm)	Method
Mekelle Area (Aynalem, Ilalla, Maileba catchments): Tekeze Basin				
Chernet & Eshete (1982)			195 (30%)	
DEVECON (1993)			195 (30%)	
WWDSE (2007)			(26%)	WATBAL
Hussien (2000)	104 km^2		57 (9%)	
Teklay (2006)	104 km^2	26	35 (5.3%)	Thornthwaite & Mather (1995)
Yihdego (2003)			53 (9.2%)	
Kahsay (2008)	104 km^2		30 (4.5%)	CMB
Zeru (2008)	104 km^2		(11%)	
Teferi (2009)	104 km^2		32 (5%)	WATBAL
Gebreegziabher *et al.* (2009)	95 m^2	65.3 (15.5%)		Field experiment
Nyssen *et al.* (2010)	121 km^2	55 (15%)		Field experiment
Nyssen *et al.* (2010)	200 ha	26.5 (8%)		Field experiment
Vandecasteele *et al.* (2011)	4 km^2		167	WATBUG (Wilmott 1977)
Girmay *et al.* (2009)	20 m^2	3.8–21%		Field experiment at Maileba MDR
Arefaine *et al.* (2012)	340 km^2	40 (7%)	66 (12%)	WetSpass
This research	14.5 km^2	48.8 (7.7%)	104.1 (16.4%)[a]	CN and Thornthwaite & Mather soil moisture balance method
			92.8 (16%)[a]	CMB
			100 (15%) for 44 days	WTF
Central Highlands of Ethiopia (Holetta Agricultural Research Center): Awash Basin				
Adimassu & Haile (2011)	110 m^2 (22 m × 5 m)	169.53 (32.3%)		Field experiment in a plot covered with wheat
Adimassu *et al.* (2014)	210 m^2 (35 m × 6)	145–325 (19–28%)		Field experiment
Selamyihun (2004)	0.078 km^2	102–258 (23–51%)		Field experiment (Vertisols)

[a]For 182 days (19 Jul 2014–16 Jan 2015), but the contribution of rainfall to runoff and groundwater recharge during dry period can be assumed minor and negligible.

Table 6 | Recharge estimation results using SMB model, and CMB and WTF methods

	P (mm)	RO (mm)	ET$_o$ (mm)	P-RO-ET$_o$ (mm)	Rech (mm)
SMB	633	48.8 (7.7% of P)	888.5	− 304.3	104.1 (16.4% of *P*)
CMB	633				92.8 (15% of *P*)
WTF	633				100 (15% of *P*)
	446				(23% of P_{rise})

2015), Abu Delaig in Sudan (weighted average 4.6 mg/l), the Sahel zone in Senegal (weighted average 2.8 mg/l), and East Africa (Rodhe *et al.* 1981). Nevertheless, it is a reasonable value for the study site considering its distance from the coast (over 300 km from the Red Sea and 1,400 km from the Indian Ocean) and low atmospheric dust during the rainy season. The chloride concentration in groundwater was 6.17 mg/l, and the effective rainfall (after subtracting runoff) during the observation period was 584.2 mm. By using Equation (6), the estimated

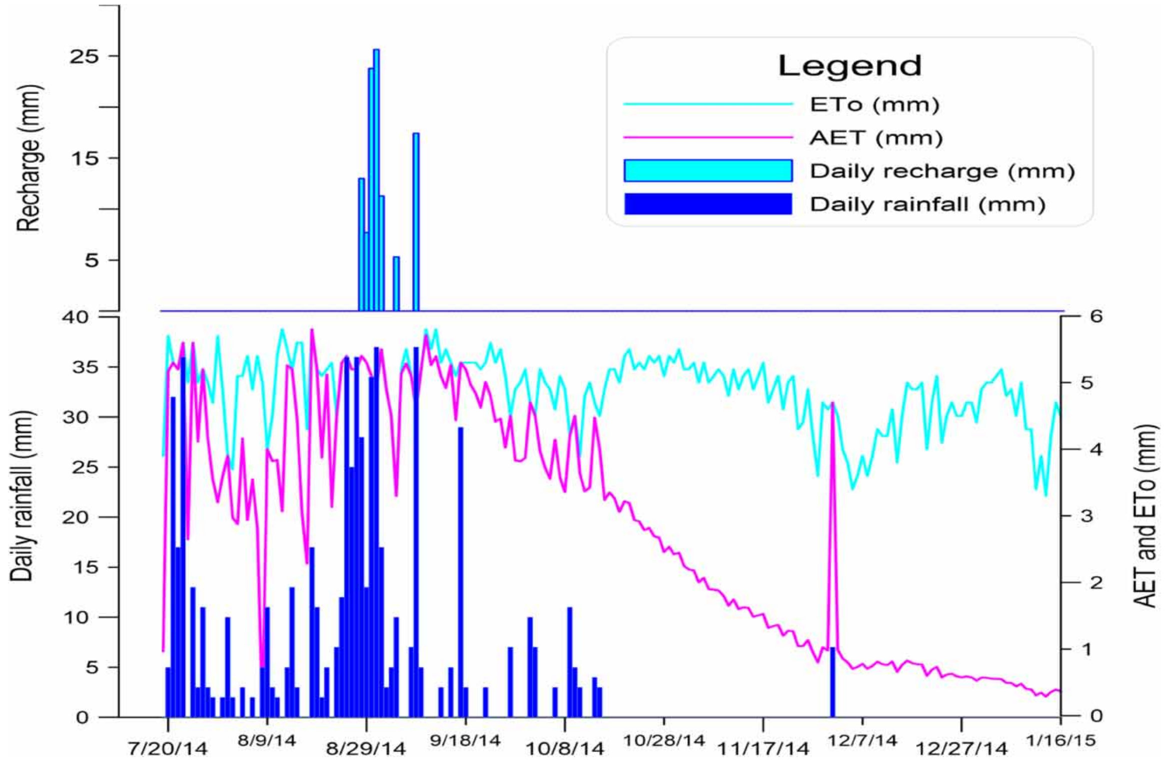


Figure 7 | Daily distribution of Potential Evapotranspiration (PET) (ET_o), AET and recharge in relation to rainfall for the observation period (19 Jul 2014 to 16 Jan 2015) of the Arato catchment.

recharge was determined to be 92.8 mm, accounting for approximately 15% of the total precipitation. In a study conducted in Indonesia (Yogyakarta City), Buana *et al.* (2023) reported a groundwater recharge of approximately 126 mm using the same method. On the other hand, Rodríguez-Huerta *et al.* (2020) estimated a recharge ranging from 43 to 143 mm in their study in Mexico, employing different methods. Considering a reference value from FAO (2009), the recharge was estimated to be around 72 mm. Furthermore, the recharge was estimated using actual measurements of WTF in a hand-dug well using a water level data logger (Figure 5). Only a portion of the observation period was considered for this method, as recharge is no longer reflected by rising water levels once groundwater starts to overflow. Based on the soil types in the recharge area and considering an average specific yield of clay and silt ($S_y = 0.05$) from Johnson (1967), the estimated recharge during the water table rise over a 44-day period (19 July 2014 to 31 August 2014) was 100 mm. This accounts for approximately 22.5% of the precipitation ($P_{rise} = 446$ mm) during the water table rise or 15% of the total precipitation during the entire observation period. In a study conducted in the upper Blue Nile Basin (Ene-Chilala watershed, 4.4 km^2) in Ethiopia, Addisie (2022) utilized the WTF method and obtained a recharge value of 89.7 mm, which accounted for approximately 16.9% of the precipitation. This finding is comparable to the results obtained in the present study.

4.4. Arato MDR water balance model

The water balance of Arato MDR can be analyzed by referring to Figure 4. By separating the known and unknown variables of the model, it is possible to solve the unknown components separately for the dry and wet seasons.

During its existence, Arato MDR has never reached its maximum reservoir level, leading to no spillway overflow. Additionally, during the observation period from 19 July 2014 to 16 January 2015, there were no irrigation or outlet releases, and livestock consumption was negligible. Given these conditions, in the water balance equation with all other components known, the direct inflow (runoff, RO) and leakage loss (Leak) remain as unknown (refer to Table 7). The estimation of RO using the CN method will be considered later to determine leakage for the entire observation period.

Table 7 | Wet observation period (19 Jul 2014 to 9 Sep 2014, 53 days) and dry observation period (17 Oct 2014 to 16 Jan 2015, 83 days)

S	Unit	Wet value	Dry value	Remark
V_{Ri}	m^3	2.5×10^4	35×10^4	19 Jul 2014 (Figure 8)
V_{Rf}	m^3	45×10^4	20×10^4	9 Sep 2014 (Figure 8)
ΔV_R	m^3	42.5×10^4	-15×10^4	
A_{Ri}	m^2	2×10^4	12×10^4	19 Jul 2014 (Figure 8)
A_{Rf}	m^2	14×10^4	8×10^4	9 Sep 2014 (Figure 8)
A_R	m^2	8×10^4	10×10^4	
ΔWL_R	m	6.00	−1.7	
ER	m^3	2.85×10^4	5.77×10^4	
PR	m	0.53	0	No rainfall during the dry period
RI	m^3	4.24×10^4	0	No direct rainfall on the reservoir during the dry period
RO	m^3	Unknown?	0	No runoff during the dry period
A_c	m^2	14.5×10^6	14.5×10^6	For design, 20.7 km^2 was considered
T_{total}	day	53	83	
ET_o	m	0.2679	0.4341	
$Out \times T_{out}$	m^3	0	0	No loss of reservoir water through the outlet during the observation period
T_{out}	day	0	0	Was not operational during the observation period
$Live \times T_{total}$	m^3	0	0	No livestock consumed water during the observation period
Leak	m/day	Unknown?	Unknown?	

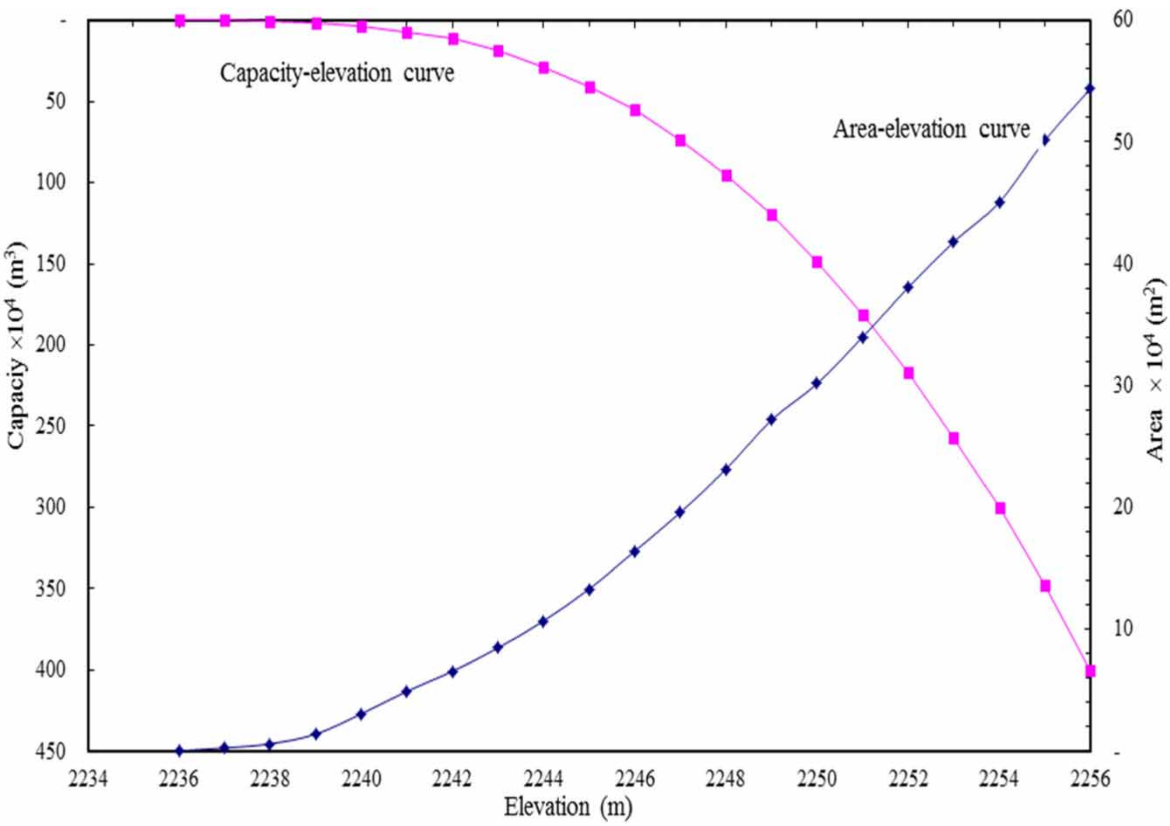


Figure 8 | Area–storage–elevation curve for Arato MDR (Hagos 1995).

The leakage component can be determined during the *dry period* when there is no inflow to the reservoir. To estimate leakage, an observation period from 17 October 2014 to 16 January 2015 was selected, considering that there was no surface or subsurface inflow and meaningful rainfall contributing to the change in reservoir volume (refer to Table 7). Continuous decline in water level during this period, attributed to evaporation and leakage, was observed. Firstly, evaporation loss and direct rainfall input on the reservoir were estimated using Equations (11) and (12), resulting in values of 5.77×10^4 and 0 m^3, respectively. Using Equation (8), Leak was estimated at approximately 112,300 m^3 over 83 days (equivalent to 1,353 m^3/day). Considering the reservoir area (10×10^4 m^2), this corresponds to 13.5 mm/day.

Assuming constant leakage over time, the leakage amount over 182 days is estimated to be around 0.25×10^6 m^3. Once the leakage loss is determined from the dry observation period, the water balance for the *wet season* (refer to Table 7) can be solved to determine runoff (RO). For this purpose firstly, the evaporation loss and direct rainfall input on the reservoir were estimated using Equations (11) and (12), resulting in values of 2.85×10^4 and 4.24×10^4 m^3, respectively.

Then, using Equation (8) and adjusting the leakage loss for the number of days in the wet season, the surface runoff (RO) is estimated to be approximately 0.64×10^6 m^3 (equivalent to 44.14 mm).

Therefore, the total inflow is the sum of direct runoff from the catchment and direct rainfall on the surface of the reservoir, which is equal to 0.68×10^6 m^3. Without considering the input from direct rainfall on the reservoir, the surface runoff (0.64×10^6 m^3) is slightly lower compared to the runoff estimated using the CN (0.71×10^6 m^3) and significantly lower than the initial design capacity of the reservoir (2.5×10^6 m^3). This observed runoff value obtained from water level sensor measurements should be considered reliable over the observation period. The slightly higher value obtained using the SCS-CN method may be attributed to various factors associated with catchment characteristics and the estimated parameters in the calculation of ET_o.

Now, with the runoff determined using the CN method and the leakage loss of the reservoir calculated using the reservoir water balance model, the leakage loss during the wet period was computed (Equation (8)).

Considering the values and unknowns presented in Table 8 and applying Equation (8), the reservoir loss due to leakage (Leak) is estimated to be 4,602 m^3/day (equivalent to 0.24×10^6 m^3 in 53 days), corresponding to 57.5 mm/day. Therefore, during the wet season, approximately 34 and 38% of the runoff estimated from the CN method and water balance method, respectively, is lost through leakage.

Table 8 | Wet season water balance (53 days) for the estimation of leakage using RO from CN method

ΔWL	6 m	Water level rise
A_R	8×10^4 m^2	
PR	0.53 m	
ER	2.85×10^4 m^3	Evaporation from the reservoir surface
RI	4.24×10^4 m^3	Input from direct rainfall
RO	0.71×10^6 m^3	
T_{total}	53 days	Total observation period
Leak	Unknown? (m/day)	

5. DISCUSSION

5.1. Water level changes

The rise in water level in the reservoir is influenced by rainfall over the catchment area and direct rainfall on the reservoir surface. The water level rise in the SHDW does not show a strong relationship with individual rainfall events. The slope of the rise remains constant regardless of the amount of rainfall on a daily basis. This could be due to continuous replenishment of the aquifer through leakage from the upstream MDR. From September onwards, the reservoir level continuously declines, while the groundwater level in the SHDW remains constant. Field observations indicate that the well was full and overflowing to the ground surface, suggesting that during the dry period, the water in the SHDW comes directly from the Arato MDR. This conclusion was confirmed by Berhane *et al.* (2016) using manual water level measurements and hydrochemical analysis. In contrast, a different situation was observed at the non-leaking Tsinkanet MDR, where there was no interaction between the reservoir and the nearby shallow aquifer, resulting in a constant reservoir level for months while the groundwater level in the shallow aquifer declined.

5.2. Reservoir evaporation

Evaporation is a natural process by which water is lost from a basin or water body. In the case of a reservoir, evaporation contributes to the overall water loss. To estimate the amount of water lost due to evaporation from the reservoir, a reference evapotranspiration value is multiplied by an empirical factor of 1.33. This factor takes into account the lack of complete meteorological data at the reservoir site. For a period of 136 days, the estimated evaporation from the reservoir was 933 mm, extrapolating this value; the annual reservoir water evaporation is approximately 1,818 mm.

Various studies have estimated the annual evaporation for different lakes in Ethiopia. For Lake Haromaya (elevation range: 1,980–2,343 m a.s.l.), Setegn *et al.* (2011) estimated mean annual evaporation of 1,882 mm using the energy balance method and 1,784 mm using the Simple Abtew equation method. For Lake Tana (elevation: about 1,800 m a.s.l.), Chebud & Melesse (2009) obtained annual evaporation estimates of about 1,430 mm using the Penman method and 1,420 mm using the Meyer method. Vallet-Coulomb *et al.* (2001) estimated annual evaporation for Lake Ziway (elevation: 1,636 m a.s.l.) at approximately 1,780 mm using the lake energy balance method and 1,870 mm using the Penman method.

These results for different lakes in Ethiopia are comparable to the estimate obtained for the Arato reservoir. It is important to note that with additional meteorological data, more accurate and refined estimates can be obtained.

5.3. Runoff and recharge processes

Understanding the hydrological processes and ensuring efficient water utilization is crucial for optimal design and operation of water harvesting schemes. However, many developing countries, including Ethiopia, face challenges in this regard due to the lack of reliable long-term data (Collick *et al.* 2009). This situation often leads to improper sizing and design of reservoirs, culverts, and storm pipes. For instance, in Tigray, out of the 92 MDRs constructed, 21 (22%) experience low inflow, and 56 (61%) suffer from siltation issues, primarily due to the lack of reliable hydrological data (Berhane *et al.* 2016).

Table 5 provides a summary of the runoff and recharge estimations using different methods in the region. The results obtained from the current study align with other research findings from the area (Table 5). It was observed that runoff starts to occur after a minimum rainfall of 13 mm. Collick *et al.* (2009) reported that runoff occurs on 20% of degraded areas in the Andit Tid and Yeku watersheds (from the Ethiopian highland area) after 10 mm of rainfall. Girmay *et al.* (2009) conducted field experiments in 2006 at Maileba MDR, also in the same region, and found runoff percentages of 3.8, 8, 10.8, and 21% for exclosure, *Eucalyptus* plantation area, grazing land, and cultivated land, respectively. Arefaine *et al.* (2012) estimated the surface runoff for the Illala sub-basin, which includes the Arato MDR, at approximately 7% of rainfall using WetSpass. The studies conducted in the Tigray region are consistent with the present results and with studies conducted in other regions (see Table 4).

Selamyihun (2004) estimated the RC for central Ethiopian highland Vertisols (in a different region) using calibrated CN. The RC values ranged from 23 to 51%, equivalent to 102–258 mm/year. Another study in the central highlands of Ethiopia by Adimassu *et al.* (2014) reported an annual runoff volume of about 145 mm (19% of rainfall) for a plot with soil bunds and 325 mm (28%) for fallow land. Adimassu & Haile (2011) reported 169.53 mm (32.3%) from a field experiment in a plot covered with wheat in the central highlands of Ethiopia. Implementation of soil and water conservation practices, as well as exclosures, reduce runoff and enhance local infiltration (Vandecasteele 2007; Walraevens *et al.* 2009, 2015; Nyssen *et al.* 2010; Vandecasteele *et al.* 2011), ultimately leading to land degradation reversal and forest regeneration in Tigray over the past three decades (De Mûelenaere *et al.* 2014; Belay *et al.* 2015).

During the observation period, the catchment yield from surface runoff was estimated at approximately 0.71×10^6 m^3, which represents only 34% of the initial design capacity of the MDR (2.5×10^6 m^3) as reported by Hagos (1995). This yield is higher than that obtained by Gebreyohannes (2009) using the WetSpass method, which was 0.096×10^6 m^3. It is important to note that the present estimation is based on site-specific data for a period of 182 days, without considering any runoff contribution during the remaining dry period of the hydrological year.

The recharge estimated using the SMB method can be considered as an annual estimate, assuming negligible recharge during the rest of the year. Similarly, the recharge from the CMB method is annual by nature, while the recharge from the WTF method represents a period of 44 days. Mekonnen *et al.* (2015a, 2015b) highlighted the significance of small sediment storage structures in relation to infiltration and sediment trapping. According to Stroosnijder (2009), who surveyed 181 medium-sized dams in the Eritrean Highlands, 31% were completely silted up, 52% were partially silted up, and only 17% did not suffer from siltation. These conditions clearly emphasize the need for integrated land and water management, tied with water harvesting planning, such as the MDRs.

5.4. Leakage from reservoir

The core focus of this research was to assess the leakage rate from the reservoir and confirm earlier conclusions using geological, geophysical, and hydrogeological approaches by Berhane *et al.* (2013, 2016). The leakage rate calculated from the water balance during the dry period was found to be high at 13.5 mm/day, compared to the results obtained by Yazew (2005) for the Gumselasa and Korir MDRs, which were 0.9 and 0.4 mm/day, respectively. Both the Gumselasa and Korir MDRs, located 35 km south and 26 km north of the Arato MDR, have low leakage rates. However, the leakage rate of the Arato MDR is approximately 15 and 34 times higher than that of Gumselasa and Korir MDRs, respectively.

During the initial design of the project, it was estimated that there would be an annual seepage loss of 9,965 m^3. However, the actual leakage amount for 182 days exceeded this estimate by about 0.24×106 m^3. Thus, approximately 15% of the inflow, as calculated using the CN method, is leaking during the 83-day dry period. The leakage rate during the wet period, considering the inflow from the CN method, was found to be 4,602 m^3/day or 57.5 mm/day, which is higher than the values obtained from the dry season water balance model (1,353 m^3/day) of the reservoir. It is observed that a rapid rise in water level in the reservoir triggers strong leakage, while leakage amounts decrease during the dry period as water levels recede.

It is important to note that the leakage estimate does not provide information about the specific location of the reservoir where the leakage is occurring. This can be better understood by considering the site geology and hydrogeology. The right abutment and central foundation of the MDR are based on dolerite, while the left abutment is on a limestone-shale-marl intercalation unit. The reservoir area is underlain by both units, with surficial Quaternary alluvial deposits found in depressions and along the river course. Based on reported hydraulic conductivities for different formations, it can be concluded that the dolerite and shale layers are less permeable compared to the bedded and fractured limestone. Thus, the limestone layers in the limestone–shale–marl intercalation unit are likely responsible for the leakage of the MDRs. Additionally, weathered and fractured top parts of all units, as well as the contact zone between the dolerite and the intercalation unit, were found to be permeable and prone to leakage.

Maps and sections providing further details on the site geo-hydrology can be found in Berhane *et al.* (2013, 2016). Conventional geological and geophysical techniques, such as vertical electrical sounding and profiling, were used to identify the leakage zone and understand its mechanisms, as reported by Berhane *et al.* (2016).

Interestingly, the leakage from the MDRs indirectly benefits local farmers by improving their livelihoods through small-scale irrigation from shallow hand-dug wells and diverted streams originating from the reservoir leakage.

By considering an average groundwater recharge of 98.9 mm from three methods, a runoff of 48.8 mm from the CN method, and an AET of 509 mm from the Thornthwaite and Mather SMB method, it is possible to compare these values with the total rainfall in the area for the given period. The total rainfall (P) was approximately 633 mm, while the sum of the three components (RO + AET + Rech) was 656.7 mm. These values are comparable and provide confidence in the application of the different methods in this area and in similar settings.

In conclusion, this research project underscores the importance of using site-specific climatic data and physical characteristics of a watershed, as well as employing different approaches and models in reservoir and water resource planning. Long-term annual water balance analysis can contribute to a better understanding of local conditions and improve the optimal planning of WHSs and other water resource management strategies.

5.5. Data reliability and uncertainties

The estimation of evaporation was indirect due to the lack of an open pan evaporimeter at the site, which could introduce uncertainties. However, the estimated evaporation was found to be comparable with estimations from other parts of the region with similar climatic and altitude conditions. Estimating groundwater recharge and reservoir leakage is challenging and associated with uncertainties. The uncertainties in the CMB method can be attributed to analytical precision and errors in determining chloride concentration. The ultimate goal of this research was to quantify leakage from the reservoir and understand the inflow, and the estimated leakage from the measured and monitored data can be considered a fairly good estimate for future planning and management in data-scarce areas.

6. CONCLUSIONS

The study site's groundwater recharge was estimated using multiple approaches. The natural recharge rates were determined to be 104, 92.8, and 100 mm using the SMB, CMB, and WTF methods, respectively. These estimates correspond to a total recharge of approximately 1.41 million m^3 for the catchment area. Assuming negligible recharge during the dry period, the results from the SMB and CMB methods can be considered as annual recharge estimates, while the WTF method covers a period of 44 days during the rainy season.

The runoff was estimated using the SCS-CN and water balance approaches. The SCS-CN method yielded a runoff estimate of about 0.71 million m^3, while the water balance approach, utilizing input data from water level sensors, resulted in a runoff estimate of approximately 0.64 million m^3.

The leakage from the reservoir was estimated using the water balance model approach for the initial part of the dry period. The calculated leakage rate was found to be 13.2 mm/day, equivalent to a total of 112,300 m^3 over the 83-day dry period (equivalent to 1,353 m^3/day). Using the same water balance model and the runoff estimated by the CN method, the leakage during the wet period was determined to be 4,602 m^3/day (equivalent to 0.24 million m^3 over 53 days), corresponding to a rate of 57.5 mm/day.

The methods employed in this study, along with accurate time series local climatic input data, can be applied in other regions to forecast water resources, particularly in areas with water scarcity and data limitations. These results and approaches are valuable for dam planners and for identifying suitable WHS.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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