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Approach of Water Balance for Evaluating the Potential Source of Water in Gidabo Dam for Irrigation Purposes

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Abstract:
The implementation of irrigation by constructing dam is the main approach to reducing poverty by increasing productivity. Many dams are multi-purpose dams that are designed to provide water for different purposes. This paper was to study the water balance approach for evaluating the potential source of water in Gidabo dam for Irrigation purposes that is located in the Abaya-Chamo sub-basin of the Rift Valley Lakes Basin. Rainfall and inflow data of 20 years (1997-2017) was used in this study. During the periods of high runoff, the water stored in the dam typically increased and overflow through the spillway occurred. There are rainy and dry seasons in the Gidabo sub-basin. The main rainy season is from April to October with a peak rainy season from April to May and a second peak rainy season from September to October. The mean annual precipitation of the sub-basin varied from 954.98 to 1843.70 mm while mean monthly variation is between 36.82 mm to 187.93 mm. The total inflow into the dam from streams and outflow from the dam were 6387 m3/s and 6170.1096m3/s respectively and the residual volume storage was 216.9904m3/s. The physical characteristics of Gidabo river catchment has similarity characteristics.

Keywords: Water balance approach, Gidabo dam, Hydrological data, Rainfall, stream flow, Ethiopia.

INTRODUCTION

Water is an inorganic, transparent, tasteless, odorless, and nearly colorless chemical substance, which is the main constituent of Earth's hydrosphere and the fluids of all known living organisms (Wikipedia, 2022a).Water is an essential resource for lives and development. The earth's hydrosphere has about 1.36 billion km3 water and 75% of the earth's surface is covered with water containing 97% salty and 3% fresh (Ali, Mushir; Terfa, 2012). Although it needs further detailed investigation, according to the current knowledge, the country has about 124.4 billion cubic meter (BCM) river water, 70 BCM lake water, and 30 BCM groundwater resources. It has a potential to develop 3.8 million ha of irrigation and 45,000 MW hydropower production (Belete Berhanu, 2013). As the human population grows, the demand for water resources will also grow. It is well recognized that water scarcity involves water stress, water deficit, water shortage and water crisis (Fulazzaky et al., 2017). The water balance states that the inflows to any water system or area is equal to its outflows plus change in storage during a time interval. In hydrology, a water balance equation can be used to describe the flow of water in and out of a system (Wikipedia, 2022b). The water regime of a region can be investigated using the water balance approach for the planning and management of available resources at the watershed scale. Water balance is commonly utilized for watershed management practices because it is vital to understand the relationship between physical parameters of the watershed and hydrological components for any watershed development effort (Dananto et al., 2022).

Today Ethiopia is struggling with poverty. The implementation of irrigation by constructing water storage dam is the main approach to reducing poverty by increasing productivity (Dananto et al., 2022). Agriculture is the main stay of Ethiopian economy. The Government of Ethiopia has given the highest and urgent priority to increasing food supply by improving and strengthening agricultural production system in the country (FDRE Ministry of Water, 2019). Ethiopia is called the water tower of Africa due to its combination of mountainous areas with a comparatively large share of water resources in Africa. Only a fraction of this potential has been harnessed so far, 1% at the beginning of the 21st century.

In order to become the powerhouse of Africa, Ethiopia is actively exploiting its water resources by building dams, reservoirs, irrigation and diversion canals and hydropower stations. The benefits of the dams are not only limited to hydropower. Many dams are multi-purpose dams that are also designed to provide water for irrigation, drinking water and flood control. However, hydropower is expected to be the main benefit of the dams (Contributors, 2021). Dams are hydraulic structures used to store, control and divert water, impounding it behind the upstream side of dam in a reservoir for different purposes (https://byjus.com/biology/advantages-of-dams/, 2022).

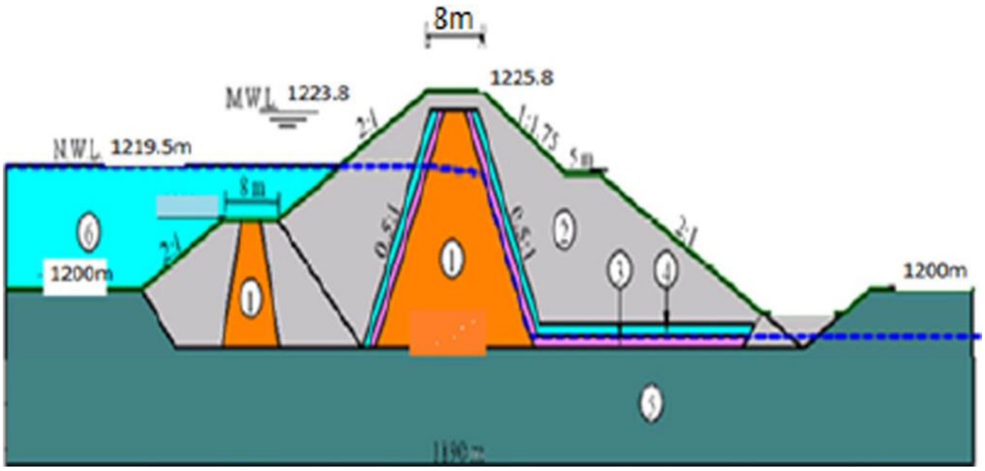
Gidabo dam is rock fill dam, which is constructed by Federal Water Works construction Enterprise of Ethiopia, to irrigate more than 14,000 ha of land (Desta & Belayneh, 2021). There are different economic developments downstream of this dam and one of this is its usage for irrigation purpose for the case of food security. Depending upon the suitability of soils the command area of Gidabo Irrigation Project has been identified on both sides of the river course. From the total study area of about 15000 hectare, leaving the uncultivable area, high lands, rock exposures and streams, the Gross Command Areas on left and right side of Gidabo river are 7113 hectare and 2763 ha respectively, totaling to 9876 ha (FDRE Ministry of Water, 2019). The Gidabo Irrigation Dam, constructed with an estimated cost of 1.1 billion Br and it irrigate 27,043ha of land, 60pc of which lie in the former region, while the rest in the latter.

This study focusses on evaluating approach water balance for the potential source of water in Gidabo Dam for Irrigation purposes. The main dam characteristics and its cross-sectional image is shown in the following table 1 and figure 1.

Table 1: Characteristics of Gidabo Dam

Dam characteristics	Value	Unit
Height of Dam	25.8	m
Catchment area	14,000	ha
Crest length	335.52	m
Storage capacity	102.4	mm^3
Submerged upstream area	1003	ha
Spillway crest level	1219.5	mamsl
Total crest length of spillway	70	m
Discharge capacity	1417	m^3/s
Spillway type	side ogee weir	-

(WWDSE, 2008)



(WWDSE, 2008)
Figure 1: Cross section of Gidabo dam

Objective of Study
The main aim of this paper was to study the water balance approach for evaluating the potential source of water in Gidabo dam for Irrigation purposes. In addition to the above main objective, the following specific objects are also carried out in this study.

1. To estimating the runoff inflow into the dam
2. To identify the sub- catchments and physical characteristics of Gidabo River catchment

Significance of Study Area
Water balance estimation is important to assess the current status and trends in water resource availability in an area over a specific period of time. Furthermore, water balance estimates strengthen water management decision-making, by assessing and improving the validity of visions, scenarios and strategies. Effective water balance approach in dam requires identification of inflow in to the dams. The knowledge of water balance of lakes and reservoirs is an essential component of water management. Today Ethiopia is struggling with poverty. The implementation of irrigation by constructing water storage dam is the main approach to reducing poverty by increasing productivity. Additionally, the significance this study is that it can be used as an important input for the following major aspects: base line for the training, research and community service for nearby Universities, non- governmental Organizations (NGOs) and other interested parties; the output of the study will also be used as information for the future NGOs and governmental offices

METHODOLOGY

Background of the Project
The project area is located in the Abaya-Chamo sub-basin of the Rift Valley Lakes Basin situated in the southern part of Ethiopia, within the administrative Regions of SNNPRS, Sidama and Oromia Regions (Tesfaye et al., 2021). The eastern part is highland having a peak of 3065 m asl and the western part is lowland where the lowest altitude is about 1156 m asl. The river originates from north eastern mountain of Soka-Sonicha, having a length of about 120 km and empties in to Lake Abaya with an annual mean discharge of 550 Mm^3(Belihu et al., 2018). It falls in Abaya district of Borena zone of Oromiya region and Dale district of Sidama zone of SNNPRS near Dilla town to East of Lake Abaya. The project area lies in the low lands, very close to the Dure and Gola marsh. It lies approximately between 6°20' and 6° 25' N Latitude and 38° 05' and 38°10' E Longitude and an average elevation of 1190 m a. s. l (see Figure 2). The study area falls within the traditional Kola

agro-climatic zone, which can be classified as semi-arid climate. The climatic data are recorded from the four observation stations Amaro Kelo, Bilate, Dilla and Bule Hora, located nearby the project area. The average minimum temperature varies from 10.2°C in Dec to 12.3°C in July and the maximum temperature ranges from 25.9°C to 30.5°C in February. The average annual rainfall recorded so far in the project command is 1303 mm with minimum of 34.9 mm in January and maximum of 208.3 mm in April (WWDSE, 2008).

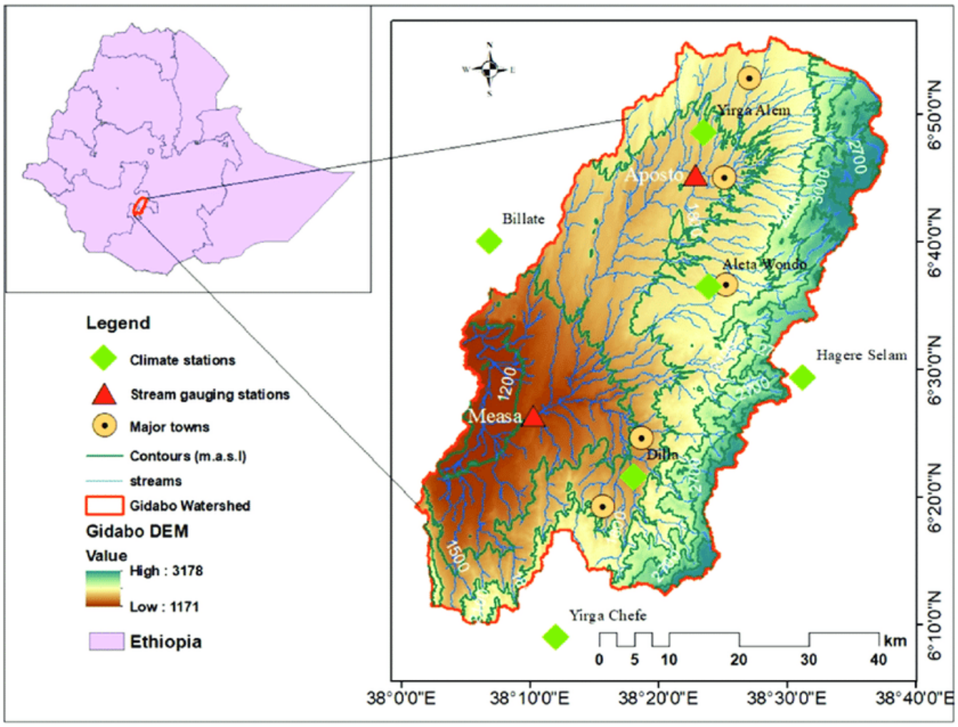


Figure 2: The locational map of Gidabo dam showing stream gauging stations, climate stations and stream

Hydrological Data Compilation

In the Gidabo river basin (total area of 3386 square kilometers), there are four stream gauging stations, namely, Aposto (area of 703 square kilometers), Kola (area of 145 square kilometers), Badessa (area of 76 square kilometers), and Measso (area of 2462 square kilometers) with data periods of 1997–2015 for Aposto, Kolla, and Badessa, whereas Measso has stream flow data from1997–2006. The daily flow data of all stations were collected from the Ministry of Water and Energy of Ethiopia. For all stations (except Measso), daily flow data were available up the year 2015, and a regression model (r2 = 0.85) was used to generate the data of Measso from its upper station Aposto. Figure 3 in below shows all the guage stations of the Gidabo River basin monitoring.

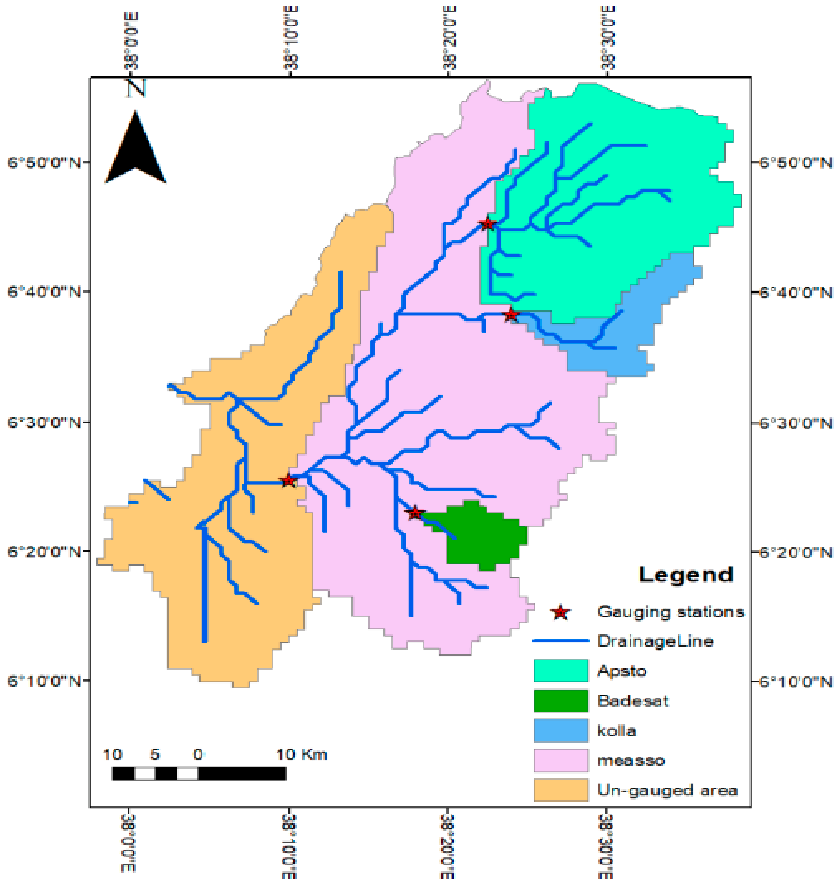


Figure 3: Gidabo river basin monitoring gauge stations

The procedure used to analyze water balance for managing a dam will vary depending on typical design of dam, river catchment area, local climate and rainfall intensity. The Gidabo Dam could be filled with water mainly from rainfall because Gidabo River, fed by small streams flowing into the dam. The spatial and temporal patterns of annual rainfall variability to show the amount of rainfalls based on the rainfall data monitored from the single rain gauge installed for covering the Dam catchment area. The overall methodology used to carry out the study was shown below in figure 4.

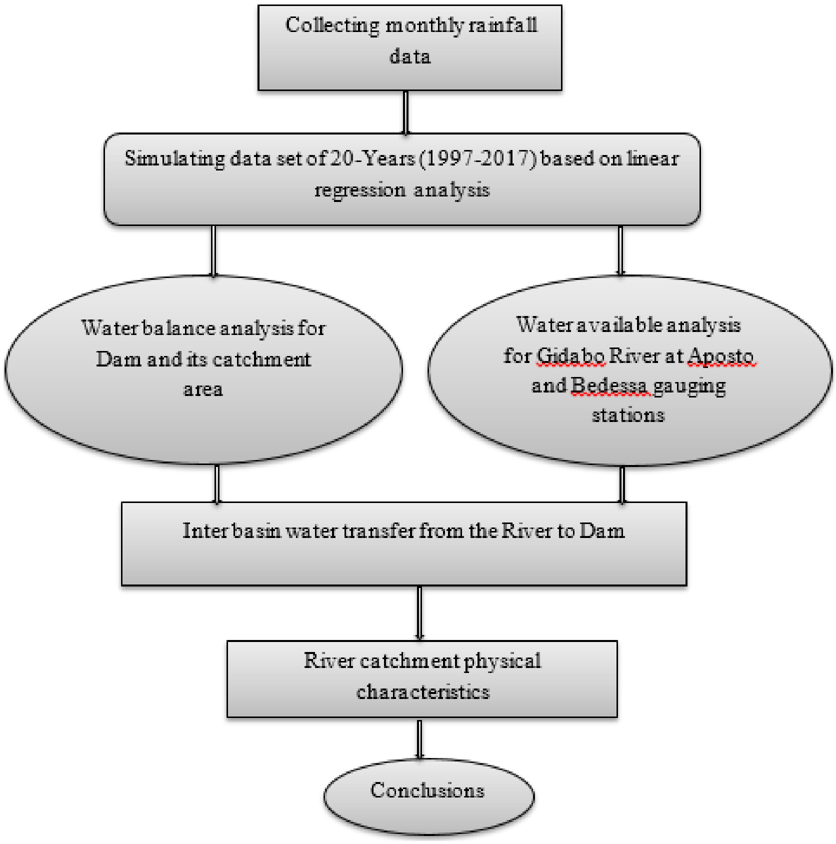


Figure 4: Flowchart of Gidabo dam water balance analysis

Rainfall Data

Climate data used for model input was collected from Ethiopian Meteorological Agency (EMA). These include rainfall, maximum and minimum temperature relative humidity. In and around Gidabo River Catchment, there are 24 stations; but, only some of them have reliable long-term data. Thesien polygon method was used to check whether the rainfall stations are influential or not. Using these criterion 13 stations was selected for further analysis the list of these stations displayed in. A monthly rainfall data of 20 years from selected meteorological stations starting from 1997-2017 was used.

Discharges for Gidabo River

The Gidabo River catchment area is one of the leading coffee production areas in Ethiopia with a basin size of 3,302 km2 (1,275 sq mi). The river is not navigable and it has no notable tributaries, but the river basin contains a sizable number of ~97 small rivers and streams in three sub-basins. The average annual discharge at its mouth amounts to 11 m3/s, with peak discharges reaching ~40 m3/s in spring and autumn, while in summer and winter the discharge can drop to 2-3 m3/s (Contributors, 2018). The river flows from the northeast and crosses the highway of Addis Abeba to Dilla at Aposto Town where it is gauged. The average flow of the river at the Aposto station is 17.35 m3/s (MOWR, 2010). The 17 years monthly mean stream flows from two stations i.e., Aposto station and Bedessa station of Gidabo River Catchment in period of 1989 - 2006 was used. The Digital Elevation Model (DEM) of 30m by 30m was collected from Ethiopian Construction Design and Supervision Works Corporation.

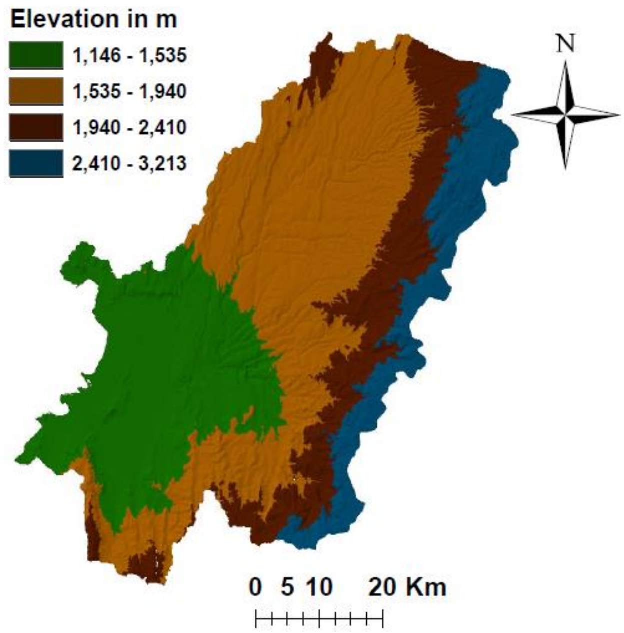


Figure 5: DEM of Gidabo River Catchment

The catchment areas of Gidabo River above the gauging stations are determined by the surface area of all lands which drains toward the river from above that point. River discharge at Aposto and Bedessa gauging stations depends on rainfall on the catchment areas and inflow or outflow of groundwater to or from the areas, stream modifications such as dams and irrigation diversions, snow and season, as well as evaporation in any temperature and evapotranspiration from the area's land and through plants. All this information must be used in a multiple regression analysis to build a regression equation of the form:

$$Q = d * P + e * S + f * N + g * T + h * IW + i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (1)$$

Where:
Q = River discharge (m^3/s)
P = Average monthly precipitation (mm)
S = Season along the year with S = 1 for summer, S = 2 for autumn, S = 3 for winter and S = 4 for spring N = Snow with N = 0 for no snow, N = 1 for snowfall and N = 2 for snowmelt
T = Temperature (°C)
IW = Water supply for irrigation (m^3/s)
d = -0.189m^3/s, e = 23.583m^3/s, f = 36.849m^3/s, g = 1.272m^3/s°C, h = -14.916 and i = -40.004m^3/s are all multiple regression coefficients.

Estimation of Water Balance for the Dam

Balancing reservoirs are required to balance supply with demand. Water balance basically looks at the balance between inputs and outputs, and thus the water balance equation is the basic formula to quantitatively study hydrology and water resources (Dawidek & Ferencz, 2014). This study used a water balance equation to calculate the variability of inflow available for Gidabo Dam, such that:

$$\text{Inflow to the dam} - \text{Outflow from the dam} = \text{Rise in the water surface of the dam} \dots (2)$$

Computing of the Inter Basin Water Transfer

In this study, the seasonal patterns of river discharge for Gidabo River need to be reviewed to make it more appealing to inter basin water transfer, according to the amount of annual water resources available. As the causality of Gidabo catchment basin characteristics according to hydro morphological reference conditions was hardly considered in a deductive approach of the inter basin water transfer an integrated analysis of the potential water availability for the rationalization of water transfer properties from River to Dam can be developed on the basis of different alternative scenarios (Galia & Hradecký, 2014).

RESULTS AND DISCUSSION

Presentation of Hydrological Data for Water Balance Analysis

A plot of the rainfall data recorded from the Gidabo Dam station versus those derived from the calculations gives a linear expression of: $P_1 = 1.284\, P_2$ with $R^2 = 0.7125$ where P_1 is the rainfall monitored at the Dam rain gauge station (in mm month_1) and P_2 is the rainfall data calculated (in mm month_1). The results in figure 6 and 7 below shows the seasonal pattern average yearly rainfall modelling for Gidabo Dam station from making long-term forecasts of 20 years (1997–2017); thus, the inter-annual rainfall variability drives the Gidabo Dam inflow variability. As a whole, the intensity of rainfall shows a decreasing trend from year to year and may result in a decreasing trend of water volume in the reservoir, in which should be potentially sufficient water available for irrigation purposes. Figure 6 and 7 in below also shows the seasonal pattern of runoff inflow into the Dam for a period of 20 years (1997–2017). Inflow into the dam in year 1998, recorded at a rate of 199.3 m^3/s was the highest inflows recorded. The lowest inflow on the record, i.e., the minimum annual streams inflow available for the reservoir, was recorded at a rate of 79.6 m^3/s in year 1999. In terms of the seasonal pattern of runoff inflow into the Dam during the last 20 years (1997–2017), the figure shows a varying trend of the inflow. But it shows decreasing trend between 2001-2003 and again from 2006-2009. Therefore, the important economic concepts that need future research attention for a scheme of integrated economic-hydrologic water management include transaction costs, agricultural productivity effects of water allocation mechanisms, inter-sectoral water allocations, environmental impacts of water allocations and property rights in water for different allocation mechanisms.

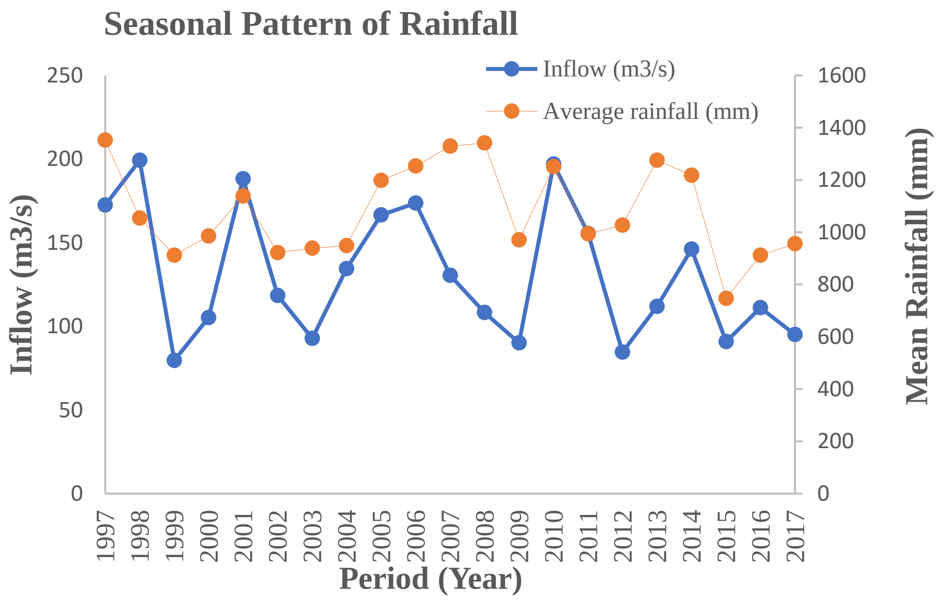


Figure 6: Patterns of inflow rainfall on the catchment area of Gidabo Dam.

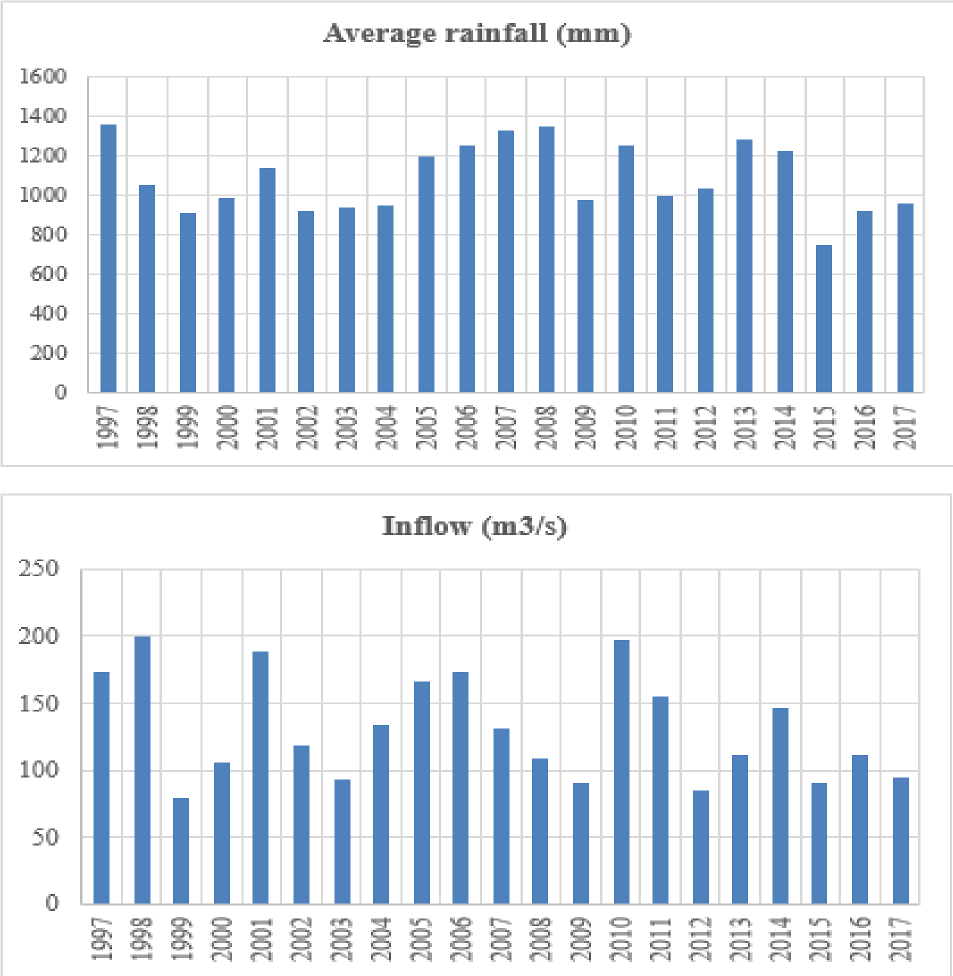


Figure 7: Extended term annual precipitation and Inflow graph (1997-2017)

Because people live mostly in the nearby of the dam, the water levels of the dam can be affected by water withdrawals for human needs. It is recognized that the withdrawal of water is one of the outflows released from the Dam.

The information about the volume of water lost through evaporation, to illustrate its significance to net water supply per year in comparison to the annual outflow from the dam, needs to be verified. The use of pan evaporation data could be useful for estimating the evaporation of the stored water, but transpiration and evaporation of the intercepted rain on aquatic vegetation are still difficult to estimate and would most likely be negligible. Even though the volume of water lost through evapotranspiration would be quite significant, the measurement of water loss from the dam based on the evaporation estimates does not accurately represent actual losses. However, the measurements and observations could confirm the significance of evaporation and help explain the influence of complex interactions among the hydro-meteorological factors that affect the water levels. For this study, evapotranspiration with a rate of 92 m^3/s of the stored water, corresponding to approximately 14.21% of the annual outflow, was estimated for the Gidabo Dam only based on the pan evaporation data. During the periods of high runoff in the years of 1998, 2001 and 2010, the water stored in the dam typically increased and overflow through the spillway occurred. There are rainy and dry seasons in the Gidabo sub-basin. The main rainy season is from April to October with a peak rainy season from April to May and a second peak rainy season from September to October. These two peak seasons are separated by the relatively small rainy season in June to August while the rest seasons from November to February are dry. The mean annual precipitation of the sub-basin varied from 954.98 to 1843.70 mm while mean monthly variation is between 36.82 mm to 187.93 mm as it shown in figure 8 below

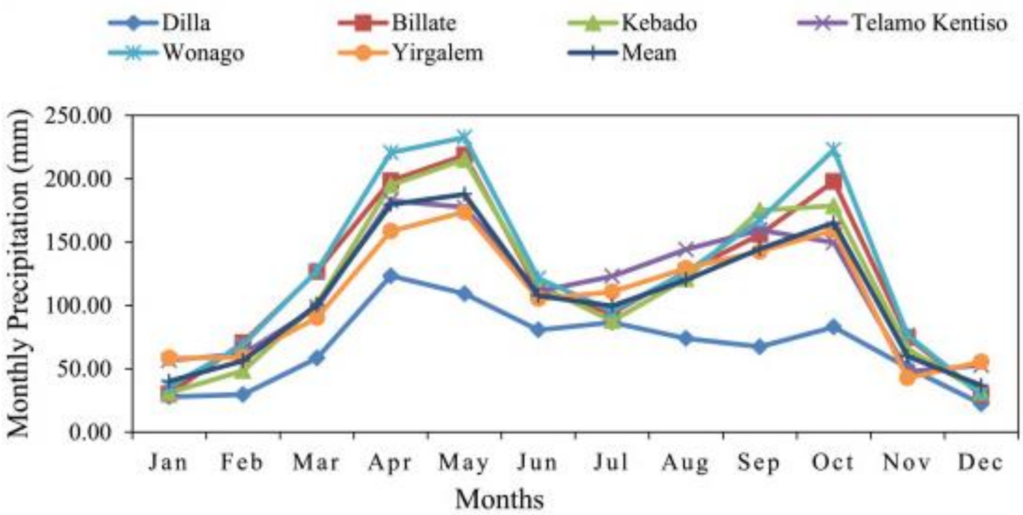


Figure 8: Spatial variation of mean monthly precipitation in Gidabo river sub-basin

As the total inflow from existing streams indicate, the composite inflow hydrograph resulting from triangular hydrographs at dam site by using standard dimensionless SCS unit hydrograph method has a peak flow of 6387 m3/s as shown on figure 9 below.

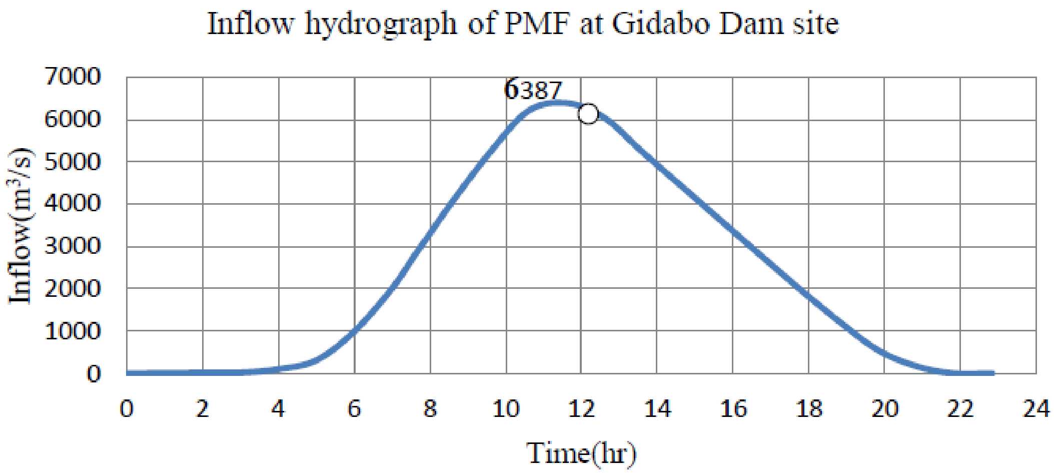


Figure 9: Total inflow hydrograph

According to the water balance analysis, a total volume of 6387.1m³/s inflow into the dam was estimated from the inflow volume from streams and a total volume of 6170.1096 m³/s outflow from the dam was estimated as the sum of outflow volumes due to evaporation (644.1375 m³/s) and water withdrawals (5525.971m³/s). The residual estimated storage of water that cannot be released from the dam should be 216.9904m³/s as indicated in table 2.

Table 2: Water balance analysis for Gidabo Dam

Items	Volume	Unit
Total volume at FSL	123.674	Mm^3
Dam volume at max. level	102.4	Mm^3
Dam volume at normal level	62.318	Mm^3
Annual mean inflow from streams to dam	6387.1	m^3/s
Outflow volume due to evaporation	644.1375	m^3/s
Water withdrawals	5525.971	m^3/s
Total volume of outflow from the Dam	6170.1096	m^3/s
Residual volume storage	216.9904	m^3/s

Sub- Catchments of Gidabo River Catchment

The physical catchment characteristics of the two gauged sub-watersheds (Aposto and Bedessa) and Gidabo River Catchment outlet were determined from 30m DEM as shown in figure 10 below.

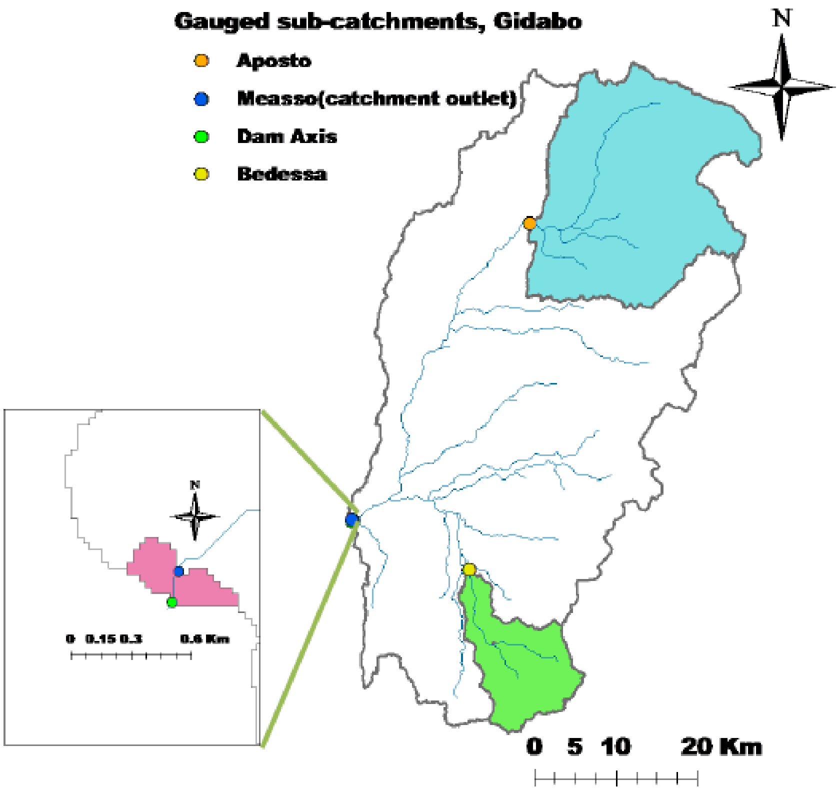


Figure 10: Sub-catchments in Gidabo River Catchment

Gidabo River Catchment Physical Characteristics

Generally, runoff in the watershed is affected by the physical catchment characteristics. These are climatic characteristics, geography and physiographic, land use and cover conditions. The climatic characteristic of Gidabo River Catchment is similar. The circularity index of both gauged catchment and Gidabo River Catchment is more or less similar. The result indicated that the catchment is elongated with smaller CI value. This result also approved by the elongation ratio. The slope of the Gidabo River Catchment also showed similarity. The drainage density of the Gidabo River Catchment also shows similarity with a low drainage density both for gauged catchment and the Gidabo River Catchment. This means the catchment drained poorly with a slow hydrologic response. The land use and land cover conditions in the Gidabo River Catchment are mainly dominated by forest land followed by crop land for gauged and for Gidabo River

Catchment. Generally, the results of selected physical characteristics of the catchments are shown in the table 3 below.

Table 3: Physical characteristics of Gidabo River Catchment

Characteristics	Apposto watershed	Bedessa watershed	Measo watershed (Gidabo outlet)
Area (km^2)	646	149.8	2947
Perimeter (Km)	174	90	416
Mean annual rainfall (mm)	1214	1495	1499
Elevation (m)	1848	1789	1851
Main stream slope (SS)	31	36.4	15
Sub-basin slope (%)	16	26	15
Land use (2018)			
FRSE (%)	75	61	55
PAST (%)	2	0.12	4
AGRL (%)	16	35	30
Drainage length (Km)	48.9	28.3	134
Drainage density	0.076	0.189	0.045
Catchment shape indices			
Circularity index (CI)	0.268	0.228	0.213
Elongation ratio (ER)	1.13	1.02	0.99

CONCLUSIONS

In this study the following points given as a conclusion. The points are:

1. Direct measurements and report data calculation was used to create a compilation of the long-term hydrological datasets for a period of 20 years (1997-2017).
2. The assessment of the trends in long-term series of hydrological data was of paramount scientific and practical significance for analyzing the amount of water available in Dam and the discharge of the river.
3. Since the amount of runoff in the catchment is affected by the physical characteristics of the catchment, identification of the physical characteristics of the catchment was of the basic thing in this study; accordingly, the climatic characteristic of Gidabo River Catchment is similar.
4. The slope of the Gidabo River Catchment also showed similarity.
5. The drainage density of the Gidabo River Catchment also shows similarity with a low drainage density both for gauged catchment and the Gidabo River Catchment; this means the catchment drained poorly with a slow hydrologic response.
6. The land use and land cover conditions in the Gidabo River Catchment are mainly dominated by forest land followed by crop land for gauged and for Gidabo River Catchment

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