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Original Research

Evaluating Water Usage and Soil Moisture Dynamics for Optimal Growth of Cavendish Bananas in Ethiopia's Vital Agricultural Regions

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Abstract

Bananas are cultivated in different parts of Ethiopia. It consumes much irrigation water throughout the year and cannot draw water from the soil. Due to these facts, the national average productivity is very low. Among field management practices, irrigation water management is a crucial aspect of banana farming. This paper aims to estimate the irrigation water demand for Cavendish bananas by evaluating the long-term decadal evapotranspiration and water balance in the key production areas of Ethiopia. The results indicated that the evapotranspiration for bananas is 2279.7, 2425.4, 2479.4, and 2468.0 mm at Assossa, Bako, Teppi, and Melkassa, respectively, during the first year of production. The total annual net irrigation calculated for bananas is 1706.3 mm at Assossa, 1609.3 mm at Bako, 1425.1 mm at Teppi, and 2024.4 mm at Melkassa during the first year of production. The total decadal gross irrigation for bananas around the Assossa area was 2843.8 mm; in Bako, it was 2682.2 mm; in Teppi, it was 2375.2 mm; and in Melkassa, it was 3263.7 mm during the first year of production. The estimated total annual volumes of irrigation water in Assossa are 32,305.9 m3/ha; in Bako, it is 30,040.2 m3/ha; in Teppi, it is 26,981.9 m3/ha; and in Melkassa, it is 38,328.6 m3/ha for the first year of production. These parameters are also estimated for each location in the second and successive years. The study concluded that much more significant amounts of banana evapotranspiration occur in study areas and exceed annual rainfall. Thus, banana growers in each area could use a nearby weather station to estimate ETo (evapotranspiration) and determine daily irrigation water requirements until a more appropriate irrigation scheduling approach is established.

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INTRODUCTION

The banana (*Musa acuminata* C.) is one of the most significant fruit crops globally (Shongwe *et al*., 2008), and it is a leading crop in world agricultural production and trade (Lamessa, 2021). Banana is an essential commercial fruit for smallholder farmers in East Africa, including Ethiopia (Gebre *et al.,* 2022). Banana is also cultivated in different parts of Ethiopia (CSA, 2020/21a; CSA, 2020/21b; Woldu *et al*., 2015). It ensures food security, generates income and creates job opportunities in the southern and southwestern regions (Alemu, 2017; Gebre Mariam, 2003; Gebre *et al*., 2022). It is cultivated for its fruit, which can be eaten ripe (Ambisa *et al*., 2019; Berhe *et al*., 2008; Woldu *et al*., 2015), and eaten cooked (Muhammad et al., 2017).

Ethiopia has large and medium-scale commercial banana farms covering nearly 3,238.83 ha of land. These farms have an estimated annual yield of 280,139.46 q with productivity of 86.47 q/ha (CSA, 2020/21b). The national average productivity of bananas in private smallholder farming is very low, less than 93.62 q ha^{-1} (CSA, 2020/21a), whereas a yield of roughly 40-60 tons/ha could be obtained under sound management in Ethiopia (Asmare *et al*., 2019; MoA, 2022). This is significantly lower than the yield of over 500 q ha^{-1} recorded at research centers (Asmare *et al*., 2019; Gebre Mariam, 2003).

Several factors influence banana fruit productivity, including genetic and environmental variables and management techniques such as irrigation and nutrient application. Water is considered the most limiting non-biological factor in banana production (Bassoi *et al.,* 2004; Carr, 2013; Paull & Duarte, 2011). Water stress is becoming a major productivity constraint for commercial and small-scale banana production due to increased rainfall variability and competition for water resources (Panigrahi *et al*., 2021; Woldu *et al*., 2015). Water deficits negatively affect bananas at each growth stage (during the early vegetative period, during the vegetative and flowering period, and yield formation) and yields. Over-irrigation of banana plantations, as seen in Melka Sedi, can cause significant damage due to salt accumulation, while under-irrigation leads to reduced yield and quality (Gebre Mariam, 2003).

Delving deeper into evaluating water usage and soil moisture dynamics is imperative to optimize banana growth and productivity. Understanding the intricate relationship between water usage, soil moisture, and the specific needs of the Cavendish banana plants is crucial for sustainable cultivation practices in Ethiopia. Efficient and effective irrigation water use plays a significant role in maximizing crop productivity. Implementing tools for regulating irrigation based on soil water content measurements can significantly contribute to sustainable water management. However, investment and maintenance costs hinder the widespread application of soil water content sensors, necessitating a comprehensive approach to address this challenge.

Allen *et al*. (1998) indicated that quantifying atmospheric conditions is one of the crop irrigation scheduling methods with very shallow meagre techniques. This method allows irrigation managers to increase water application efficiency based on the seasonal plant water requirements and soil processes. There is limited documented information on irrigation scheduling and water requirement studies in banana farming in Ethiopia. No theoretical and practical attempt was made to estimate irrigation scheduling for Cavendish banana fruit in Ethiopia. Therefore, this research estimates banana crop water requirements using long-term climate data to support irrigation scheduling decisions in banana-producing areas of Ethiopia.

MATERIALS AND METHODS

Description of the study areas

This study uses long-term historical climate data for major banana-producing areas such as Assossa, Bako, Teppi, and Melkassa. Geographically, they are located at 10.0620°N and 34.5473°E, 9.1248°N and 37.0588°E, 7.1967°N and 35.4289°E, and 8.4°N latitude and 39.31°E longitude respectively. They have altitudes of 1570, 1743, 1200, and 1550m above sea level, respectively. The corresponding average annual rainfall is 1275, 1238, 1559, and 763mm. The maximum and minimum temperatures for Assossa are 28.7°C and 14.2°C, for Bako are 27.0°C and 13.00°C, for Teppi are 30.23°C and 16.09°C, and for Melkassa are 28.4°C and 14.0°C, respectively. The dominant soil types in Assossa are clay soil (Mekonnen & Adhanom, 2021; Wakwoya *et al*., 2023); in Bako are clay soil (Berhanu and Eyasu, 2021); in Teppi are clay loam (Beniam and Tesfaye, 2016) and in Melkassa are silty loam (Liben *et al*., 2017). The soil field capacity and permanent wilting points are 0.40 and 0.22 for Assossa, 0.40 and 0.22 for Bako, 0.29 and 0.18 for Teppi, and 0.40 and 0.22 for Melkassa. Although each location has different soil types, the dominant soil types were selected to represent each location.

Although banana grows in broader areas of lowland and dry parts of Ethiopia, this study focused on areas where long-term historical climate data is available, and the daily long-term historical weather data were used to compute each study area's decadal reference evapotranspiration (ETo). Long-term weather parameters of thirty years, 1987-2017, were used for this study. The historical weather data were collected from various sources, such as the Ethiopian Institute of Agricultural Research (EIAR) and the National Meteorological Agency. The key reason for selecting study areas is that the Cavendish banana type is the most produced in Ethiopia's lowland areas as it requires base temperatures of 14^{0}C (Paull and Duarte, 2011). A mean temperature of about 27°C is optimal for growth, and the minimum temperature for adequate growth is about 16°C, below which growth is checked and shooting delayed (www.fao.org/land-water/databases-and-software/crop-information/banana/en). These areas are among Ethiopia's major commercial Cavendish banana-growing lowland areas.

Figure 1 depicts the geographical descriptions of each study location.

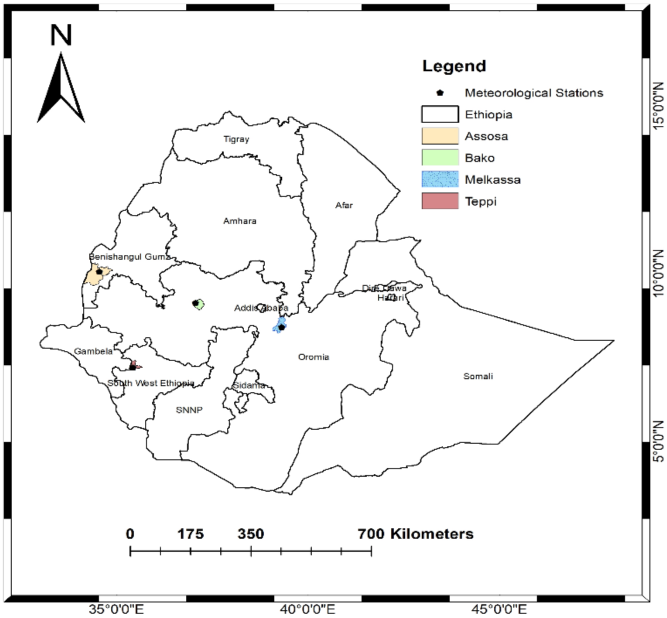


Figure 1: Locations of the study areas

Methods of estimation and calculation

Evapotranspiration

Real-time evapotranspiration-based irrigation scheduling requires accurate evapotranspiration estimation and irrigation water requirements with the shortest period intervals. The crop water requirement is the amount of water equal to what is lost from a cropped field by the ETc and is expressed by the rate of ETc (mm/day).

Water balance equation

A simple water balance equation calculates crop water requirement in a lysimeter (USDA, 1997).

$$ETc = Pe + I + C - \Delta S - D \qquad (1)$$

Where ETc = Crop Evapotranspiration, Pe = Effective rainfall, I = Applied net irrigation, C Capillary contribution or water from shallow groundwater, ∆S = Soil water storage in the root zone at a given time, and D = Water lost due to deep percolation. All the input and output in the water balance equation are in mm/day.

Net irrigation

The net irrigation requirement is the water required to refill the root zone soil water content back up to field capacity. This amount, the difference between field capacity and current soil water level, gives the net amount of irrigation water to apply.

Assuming C, ∆S, and D in the root zone are zero, then net irrigation is computed as described by Allen *et al*. (1998)

$$I = ETc - Pe \qquad (2)$$

Evapotranspiration rate (ETc)

For ET-based irrigation scheduling, the actual decadal evapotranspiration rate (ETc) is calculated by multiplying ETo and banana crop coefficient (Kc) values appropriate for the plant ages in the field.

$$ETc = ETo * Kc \qquad (3)$$

ETo = Reference Evapotranspiration, and Kc = Crop coefficient

Reference Evapotranspiration (ETo)

Reference Evapotranspiration (ETo) was calculated using the FAOPenman–Monteith equation for the weather data. The Penman–Monteith equation formula is as follows (Allen *et al*., 1998).

$$ETo = \frac{0.40\, \Delta\, (Rn - G) + \gamma\, \frac{900}{T + 273} U2\, (es - ea)}{\Delta + \gamma\, (1 + 0.34\, U2)} \qquad (4)$$

Where ETo = Reference evapotranspiration (mm/day), Rn = Net radiation at the crop surface ($MJ/m^2/day$), G = Soil heat flux density ($MJ/m^2/day$), T = Mean daily air temperature at 2 m height (°C), U2 = Wind speed at 2 m elevation (m/s), es = Saturation vapour pressure (kPa), ea = Actual vapour pressure (kPa), es - ea = Saturation vapour pressure deficit (kPa), Δ = Slope of vapour pressure curve (kPa/°C), Ύ = Psychrometric constant (kPa/ °C). The equation uses standard climatological solar radiation records (sunshine), air temperature, humidity, and wind speed.

Determination of effective rainfall

The primary rainy season that requires daily estimation of effective rainfall in many parts of Ethiopia starts in July and lasts until September/October. In many areas, seasonal rain precipitation (P) might provide part of the water requirements during the irrigation season. The amount of rainwater retained in the root zone is called effective rainfall (Pe) and should be deducted from the total irrigation water requirements estimated (USDA, 1997). It can be roughly estimated using the formula as indicated in the following:

$$Pe = 0.8\, P \text{ where } P>75 \text{ mm per month} \qquad (5)$$

$$Pe = 0.6\, P \text{ where } P<75 \text{ mm per month} \qquad (6)$$

Where d = water stored in the root zone and Water Applied (gross) is the irrigation water. Most Ethiopian farmers use furrow irrigation systems with various application efficiencies (MoA, 2011; Alemeseged *et al*., 2020). Different studies on the application efficiencies in Ethiopia indicate figures in diverse areas. Knowing the irrigation system's efficiency is essential to calculate the plant's gross irrigation water requirement. The gross irrigation water requirement for banana production will be estimated by taking the application efficiency of a short, end-drenched furrow basin irrigation with 60% application efficiency.

Irrigation efficiency

Irrigation application efficiency is the ratio of irrigation water stored in the root zone to the total irrigation water delivered to the crop. The amount of water stored in the root zone is estimated as the net irrigation dose (d). However, during the irrigation process, a considerable amount of water loss occurs through evaporation, seepage, and deep percolation. The amount lost depends on the efficiency of the system. Irrigation field application efficiency is expressed as (USDA, 1997):

$$Ea = \frac{d}{\text{Water Applied (gross)}} \times 100 \qquad (7)$$

Where, d = water stored in the root zone and Water Applied (gross) is the irrigation water. Most Ethiopian farmers use furrow irrigation systems with various application efficiencies (MoA, 2011; Alemeseged *et al*., 2020). Different studies on the application efficiencies in Ethiopia indicate different figures at diverse areas. Knowing irrigation system efficiency is essential to calculate plants' gross irrigation water requirement. The gross irrigation water requirement for banana production will be estimated by taking the application efficiency of a short, end-drenched furrow basin irrigation with 60% application efficiency.

Gross irrigation water requirement

The amount of water stored in the root zone is estimated as the net irrigation. However, during the irrigation process, considerable water loss occurs through evaporation, seepage, deep percolation, etc, from the furrow basin irrigation method. The amount of water lost during irrigation depends on the system's efficiency. Gross irrigation water requirement was estimated as per the equation suggested by USDA (1997):

$$GI = \frac{ETc - Pe}{Ea} \qquad (8)$$

Where, GI = Growth irrigation, Pe = Effective rainfall (mm) and Ea = Application Efficiency

Total available water

The total available water in the root zone is the difference between the water content at field capacity and wilting point (Allen *et al*., 1998):

$$TAW = 1000\ (\theta_{FC}-)\ \ Zr \qquad (9)$$

Where TAW = is the amount of water that a crop can extract from its root zone (*p*), and its magnitude depends on the type of soil and the rooting depth (Zr) (Allen *et al*., 1998).

Accessible soil moisture

The fraction of TAW that a crop can extract from the root zone without suffering water stress is the readily available soil water (Allen *et al*., 1998):

$$RAW = \rho\ TAW \qquad (10)$$

Where: RAW = Readily available soil water in the root zone [mm], *p* = Average fraction of Total Available Soil Water (TAW) that can be depleted on the root zone before moisture stress (reduction in ET) occurs (0 – 1).

Irrigation intervals

Irrigation frequency is the number of days intervals between two consecutive irrigations, and it can be computed using the formula suggested by USDA (1997):

$$\text{Irrigation interval (I)}\ \frac{\text{Net IR}}{\text{ETc}} \qquad (11)$$

Where: I = Irrigation Interval (days), Net IR = Net irrigation requirement (mm), ETc = Irrigation water requirement (mm/days).

The Volume of irrigation water

The Volume of irrigation water was calculated from the gross irrigation water requirement (depth of water) for one hectare of banana plantation (USDA, 1997).

$$V = A * D \qquad (12)$$

Where: V = Volume of irrigation water (m^3), A = Area in m^2, and D = Depth of water (m).

This research estimated the irrigation water for banana crops planted on one hectare, assuming that banana plants are grown at 1.5 m spacing with 1m mater radius basin/ring irrigation. Thus, the wetted area under furrow basin/ ring irrigation is, therefore, πr^2, equal to 3.14 m^2 and 67*67 plants on one hectare. Wetted area in one hectare is assumed to be 3.14 m2 *67*67 = 4489 m^2; that means out of one hectare, a total of 4489 m^2 area continuously fully irrigated during irrigation and small water savings may be obtained because water is applied only within the limited radius leaving the remaining part of the soil dry (MoA, 2011). Fruit crops are irrigated by constructing basins (young tree) or rings (big tree) around trees; both methods involve only partial wetting of the soil surface; a considerable amount of water is saved, and the irrigation efficiency is found to be high (MoANR, 2011). The total irrigated area is covered by banana canopy coverage, indicating a low location to irrigate during a few months until the maximum canopy development is attained.

Determining Kc and banana growth characteristics for irrigation scheduling

The Kc_{ini} and Kc_{end} for evergreen non-dormant fruit trees are often not different, where climatic conditions do not vary much, as it happens in tropical climates; under these conditions, seasonal adjustments for climate may therefore not be required since variations in ETc depend mainly on variations in ETo (Allen *et al*., 1998). Once the first ratoon is allowed to grow in Cavendish banana, then maximum Kc was taken and kept constant throughout the plantation life, which can be up to 20 years or more depending on correct de-suckering and control of pests, diseases, and other field management practices (www.fao.org/land-water/databases-and-software/crop-information/banana/en). Allen *et al*. (1998), gave the Kc of a single banana plant. In contrast, the Kc of the banana mat is not worked out as bananas have overlapping ratoons perennial plants. The banana was not included in the text of Advances in Irrigation Agronomy prepared by Carr (2013). In contrast, the details of other fruits were reviewed.

Each Cavendish banana plant growth cycle has three stages: vegetative development (nearly six months), flowering (≈3 months), and fruit stage (≈3 months), depending on the prevailing temperatures in the area (Paull and Duarte, 2011). This means the time between planting a banana plant and the harvest of the Cavendish banana bunch is assumed to range from 10 to 13 months, depending on the temperatures of growing conditions. Through allowing successive one sucker every 3 to 4 months, there is a consecutive harvest of Cavendish banana bunch every 3 to 4 months from each mat as practiced in the lowland areas of Ethiopia such as Arba Minch, Teppi, Bako and other low-lying areas of the country (Asmare *et al*., 2019; Gebre Mariam, 2003). One can get all growth stages of banana plants (usually three plants of various ages) in the farm on each mat nearly seven months after transplanting, leading to the use of maximum and constant Kc after seven months throughout the plantation life.

Many researchers took the banana plant as an annual crop with initial, development, mid-stage, and late growth stages totalizing with LGP nearly 365 days (Paull and Duarte, 2011). However, a banana plantation is a long-term fruit crop where one can practically overlap all growth stages from different plants on the same mat simultaneously. Thus, there might be much more daily irrigation water demand in reality than estimated for one plant in this paper and other FAO publications for all study areas as all papers estimated for single banana plant initiating further detailed water requirement studies required for – rather than multiple of banana shoots with all and each growth stages occur together on the same mat at the same time throughout the lifespan of banana plantations.

Table 1: Typical crop coefficients (Kc) for banana fruit transplanted in the first week of July (days after transplanting) in Ethiopia.

A	**July Aug. Sept.**	**Oct. Nov Dec.**	**Jan. Feb. Mar Apr. May June**
Kc	0.5 (Allen *et al.,* 1998)	1.2 (Allen *et al*., 1998)	1.25 (7 months and greater)
Growth characteristics	Newly planted and young plants (initial stage)	The first follower can grow while the main plants prepare for flowering.	The second follower is allowed to grow while the first follower is ready for flowering, and the main mother plants set fruit and fruit development period (multiple shoots)-then constant Kc is used.

Bananas are transplanted in July in most major parts of Ethiopia. July, August, and September are the rainy season, and irrigation is considered to be not required during this period. The value of Kc for banana might be small, 0.5 after transplanting, and then onwards from October, which is the start of the dry season where irrigation should be applied. Here maximum Kc value of 1.25 is used for the main and all following ratoon crops as banana suckers grow together one after the other for years. The ranges of maximum effective rooting depth (Zr) for bananas are (0.7 m), and Soil water depletion fraction for no stress (p), MAD (Management Available Depletion) for banana crop is 0.35 (Allen *et al*., 1998), but since all the areas are hot and dry MAD of 0.30 was adopted assuming no stress through this study (for this study, maximum rooting depth for banana plant is taken as 0.7 m when full canopy is attained).

Data collections

Decadal long-term weather Data

This study used primary and secondary data collected from each location of the study area.

Long-term weather parameters (30 years, 1987-2017) were taken from the Ethiopian Institute of Agricultural Research (EIAR) Weather Stations (Assossa, Bako, Teppi, and Melkassa Weather Stations). The long-term decadal historical weather data from the study areas were used to compute decadal reference evapotranspiration (ETo) and net and gross irrigation requirements of bananas for each of the specific areas.

This study uses the water balance and ET–based estimation of irrigation water requirement approach for irrigation scheduling for Cavendish banana. Estimate of evapotranspiration-based irrigation scheduling includes determining crop evapotranspiration (ETc), net irrigation requirement, reference evapotranspiration (ETo), effective rainfall, irrigation efficiency, growth irrigation water requirement, total available water, readily available soil water, and total volume of water. Water balance calculations cannot begin until soil water content in the root zone is known. It may be established before or after crop emergence. Once verified, the soil water content of successive days can be estimated using the water balance equation. Crop water consumption or evapotranspiration accounts for the biggest subtraction of water from the root zone; deep percolation and runoff also subtract water from the soil, while rainfall and irrigation provide the major additions (Allen et al., 1998).

Soil water-holding characteristics of study sites

The soil physical properties required for estimating irrigation water requirements for each study location were collected from primary and secondary sources. Personal observations were made throughout the year with frequent fieldwork in all study areas

RESULTS AND DISCUSSIONS

Rainfall and potential evapotranspiration

The long-term historical climate data analysis showed that each location's total decadal potential evapotranspiration (ETo) was much greater than the total annual rainfall received by each site. This indicates the high evaporative demand of the atmosphere in all banana production areas for most of the year, except during the short rainy season when the daily evaporative demand is relatively lower than the daily total rainfall. The trends of rainfall and potential evapotranspiration in Assossa, Bako, Teppi, and Melkassa are indicated in Figure 2(a-d) below.

The absence of adequate rainfall for most of the year, particularly during the cool-dry period from October to early January and the hot-dry period from mid-January to May/June, results in a water deficit for banana farming. This indicates the need for full irrigation throughout the dry period, starting in September and lasting until May/June. Detailed investigations on Cavendish banana water requirements and irrigation scheduling are essential to produce high yields and fresh fruits of high quality while saving water and maximizing economic benefits.

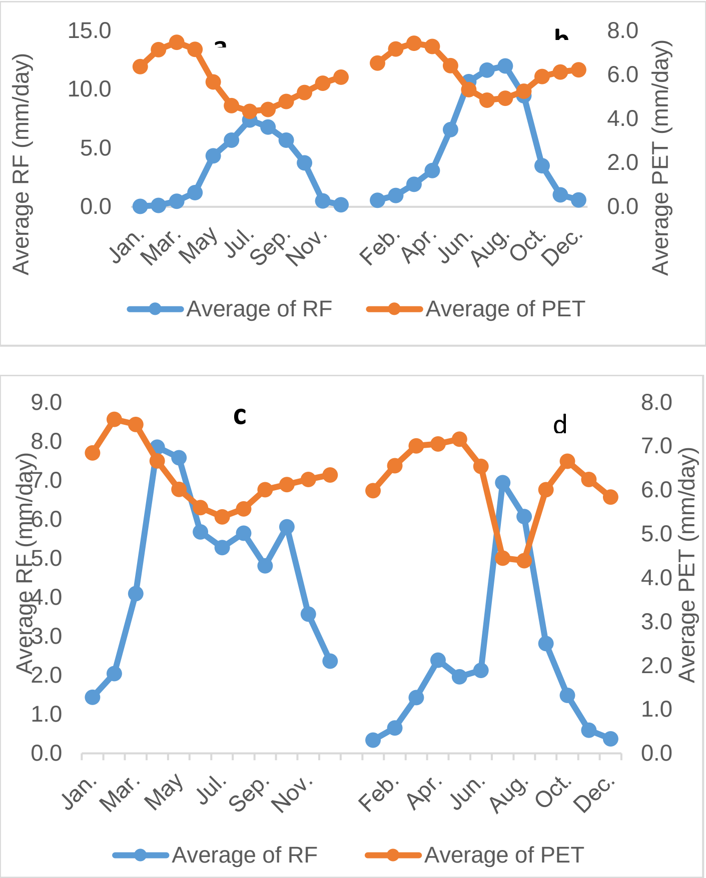


Figure 2: Long-term rainfall and potential evapotranspiration a) Assossa, b) Bako, (c) Teppi and d) Melkassa

Soil water holding characteristics

The soil moisture content indicates the amount of water present in the soil. Understanding soil water content and its threshold level is essential for effective irrigation management. It influences plant growth, soil temperature, the transport of chemicals, and groundwater recharge. Depending on this fact, the study areas' soil water-holding characteristics were estimated and shown in Table 4. The effective root depth of the banana plant was measured to be 0.70 m. The respective soil bulk densities were used to calculate each area's total soil moisture content. A depletion fraction of 0.3, as stated by Allen *et al.* (1998), was used for the computations.

Table 2: Soil water holding characteristics of study locations.

No	Location	FC (m^3/m^3)	WP (m^3/m^3)	BD (gm/cm^3)	*p*MAD	TAW (mm)	RAW (mm)
1	Assossa	0.40	0.22	1.35	0.3	126	37.8
2	Bako	0.40	0.22	1.35	0.3	126	37.8
3	Teppi	0.29	0.18	1.45	0.3	77.0	23.1
4	Melkassa	0.36	0.21	1.45	0.3	105	31.5

FC = soil water content at field capacity, WP = soil water permanent water holding capacity, BD = soil bulk density, TAW = total available water, RAW = readily available water, PMAD = manageable depletion level

Irrigation Water Requirement and Irrigation Scheduling

Rainfall is vital for agricultural production systems in arid and semi-arid conditions. Its total amount over specific periods, intensity, and spatial and temporal distributions characterizes it. In many humid and tropical locations, annual rainfall is lower than evapotranspiration. Therefore, crops must be irrigated for optimal production (Fares, 2009). In all four study locations, the total banana ETc (evapotranspiration) is much greater than the annual rainfall. Although the rainfall is concentrated in nearly three months, bananas still require full irrigation in all production areas in Ethiopia. Good irrigation practices should be implemented to ensure effective water distribution within the root zone. The amount of water plants use varies due to the climate and depends on their size, crop load, growth stages, and phenological patterns.

Banana irrigation scheduling is done in two stages: the first year of plantation, where Kc varies, and the 2nd and consecutive years for well-managed banana plants, where Kc is constant. Although estimating daily irrigation water requirements is more accurate than estimating weekly requirements, estimating weekly requirements is more accurate than estimating decadal and monthly irrigation requirements. For simplicity, assessing and calculating the decadal ETc, net irrigation water requirement, decadal gross irrigation, decadal irrigation volumes, and decadal irrigation intervals for Cavendish banana in four production areas, the following information is provided below:

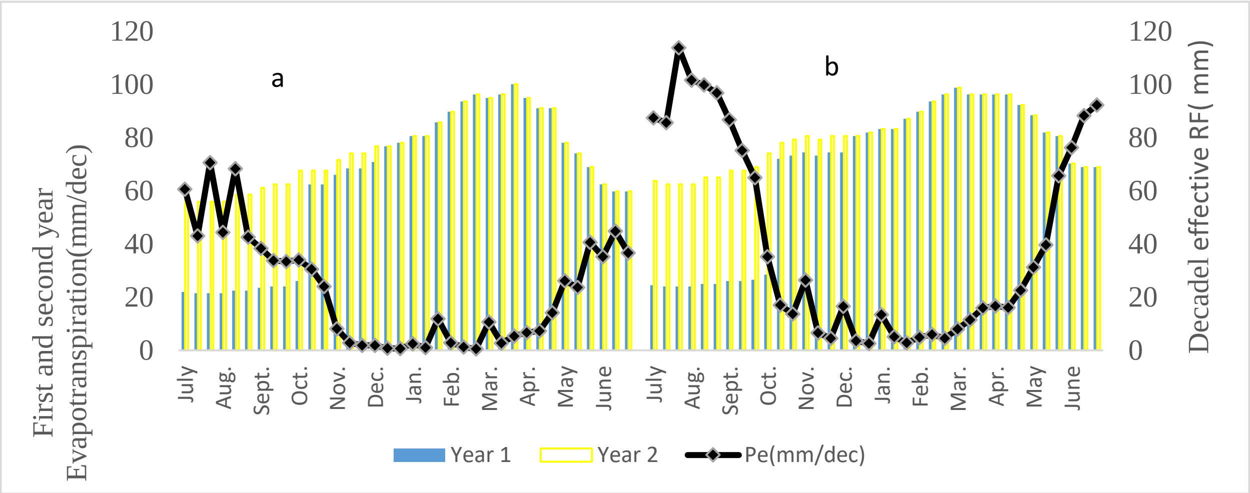
Crop Evapotranspiration (ETc) and Effective Rainfall

Assossa receives the lowest decadal rainfall (0.5mm/dec) in February and the highest in July (70.6mm/day). The lowest decadal crop evapotranspiration (ETc) was also estimated in July (21.5mm/dec), and the highest was in March for the first year of banana production. For the second year, bananas estimated lowest and highest ETc were 55.9 mm/dec and 100.1 mm/dec in July and March, respectively. Figure 3(a) shows the variation of effective rainfall and crop evapotranspiration in Assossa for the first and second years of banana production throughout the year. The long-term average annual rainfall at Assossa is estimated to be 1275 mm per year, while a total of 2279.2 mm and 2679.3 mm of ETc is required for Cavendish banana production during the first and second year, respectively (Table 3).

Bako's estimated lowest and highest decadal effective rainfall was 2.6 mm/dec and 113 mm/dec in December and July, respectively. Maximum and minimum decadal crop evapotranspiration of 24 and 62.4 mm/dec in July for the first and second year, and 98.8 mm/dec in March for both years, were estimated. Figure 3(b) shows the variation of effective rainfall and crop evapotranspiration in Bako for the first and second years of banana production throughout the year. The long-term historical climate data at Bako indicates that the area receives an average annual rainfall of 1458.4 mm. However, Cavendish banana fruit requires 2425.4 mm/annum (ETc) during the first production year. Similarly, an estimated 2867.8 mm/annum of ETc was calculated during the second and subsequent production years. (Table 3)

The rainfall around Teppi is characterized by its total amount over specific periods and issues related to intensity and its spatial and temporal distributions. There is the highest rainfall in the Teppi areas, and banana production is entirely rain-fed (Woldu et al., 2015). In Teppi, the lowest estimated decadal rainfall and ETc were 3.6 mm/dec and 26.5 for the first year, and 68.9 mm/dec and ???? for the second year of banana production in September and December. The highest estimated ETc was 101.4 mm/dec for both in February. Figure 3(c) shows the variation of decadal effective and ETc for the banana life cycle. A total annual average rainfall of 1093mm was recorded from long-term climatic data for the Teppi area, while a total of 2479.4 mm/annum ETc was estimated for the Cavendish banana during the first year of production (Table 9). Similarly, a value of 2988.7 mm ETc was calculated during the second and subsequent years of banana production at Teppi (Table 3)

The estimated effective rainfall and ETc are shown in Figure 3(d) for Melkassa. The Melkassa received the lowest decadal rainfall of 1.4 mm/dec in December and 39.6 mm/dec in September. The lowest decadal ETc was 26.5 mm/dec for the first year and 68.9 mm/dec for the second year. The highest ETc recorded was 93.6 mm/dec for both years. The analysis of long-term climatic data in the Melkassa area showed an average annual rainfall of approximately 763 mm. Additionally, during the first year of banana production, 2468.0 mm of ETc (evapotranspiration) was recorded (Table 11). Similarly, 2855 mm of banana ETc was calculated during the second and subsequent production years (Table 3).



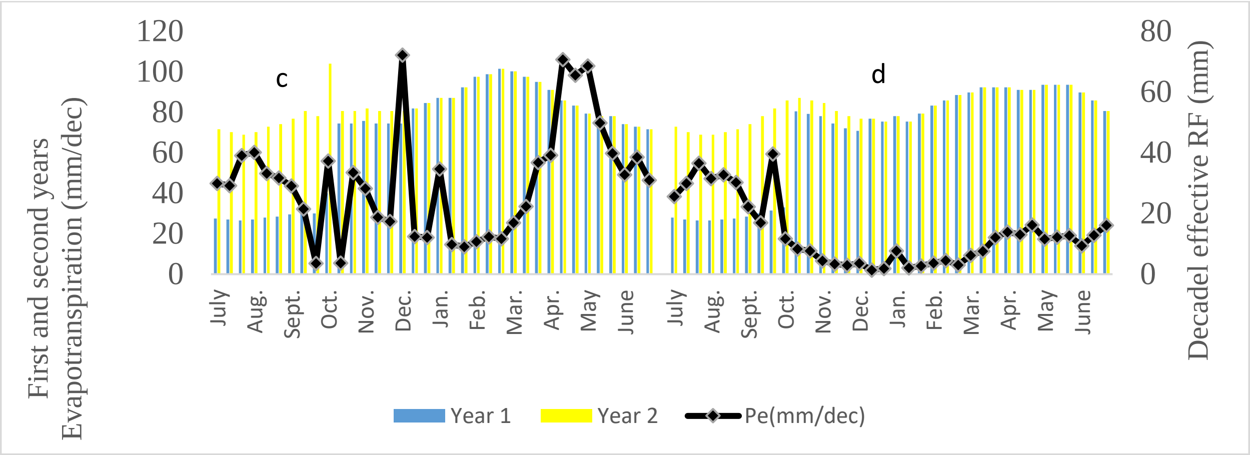


Figure 3: Estimated decadal evapotranspiration and effective rainfall a) Assossa, b) Bako, Teppi c) Teppi, and d) Melkassa

Net Irrigation and Gross Irrigation

The estimated annual net irrigation for each decade from November to April is highest during the first year of Cavendish banana production, as shown in Figure 4(a), totalling 1706.3 mm per year for the first of production (Table 3). In contrast, the estimated net irrigation is negative because of the highest effective rainfall from July to October. In the second year, the lowest net irrigation occurs in July, while the highest net irrigation is observed from February to March (figure 4a), totalling 1893.6 mm per year during the second and subsequent years (Table 3). The decadal gross irrigation at Assossa has low values, estimated to be around 37 mm, during July, August, September, and October. On the other hand, high gross decadal irrigation is estimated from November to May, with a total of 2843.8 mm per year during the first production year (Table 3). An estimated 3156.5 mm of irrigation is required annually during the second and subsequent years of Cavendish banana production.

Based on the long-term historical data record, the rainy season at Bako typically begins in the second decade of June, when one can stop irrigation. The average annual net irrigation for Cavendish banana production in the Bako area is highest during February, March, and April, with a rate of 91.7 mm per decade, as shown in Figure 4b. In the first year of production, the total net irrigation requirement is estimated to be 1609.3 mm/year. The estimated total net irrigation requirement for the second and subsequent production years is 1689.0 mm/ (Table 3). In the first production year, the annual gross irrigation water requirement for Cavendish banana production in Bako was high in February and March (Figure 4b). It was estimated to be 2682.2 mm per year. In the second and subsequent years, the irrigation water requirement is calculated to be 2815.0 mm (Table 3).

The decadal net irrigation water requirement for Cavendish banana production in the Teppi area is at its maximum from January to March during dry decades in the first year of production (figure 4c), totalling 1425.1 mm/year (Table 3). A total of 1895.7 mm of net irrigation is estimated annually for the second and subsequent years. The estimated gross irrigation (GI) for Cavendish banana production in the Teppi area reached 153 mm during the third decade of February, totalling 2375.2 mm/annum during the first year of production. Similarly, high decadal gross irrigation was recorded during the first production year in February and March. The same pattern was observed in the second and subsequent production years, with a total annual requirement of 3159.5 mm.

The estimated decadal net irrigation requirement for Cavendish banana production at Melkassa ranges from the highest of 80 mm/dec to the lowest of 0 mm/dec, with a total of 2024.4mm per annum during the first year of banana production as shown in figure 4 d below. Similarly, the highest decadal net irrigation was recorded in Feb. and March, with a total of 2377 mm per annum during the second and subsequent production years (Table 3). The decadal gross irrigation estimation at Melkassa was very high from November to May, with some decades reaching as high as 140 mm/dec (figure 4d) and a total of 3263.7 mm/annum during the first production year. At the same time, the highest decadal gross irrigation was recorded from Feb to June (Figure 4d), with a total of 3961.3 mm/year during the second and subsequent years (Table 3).

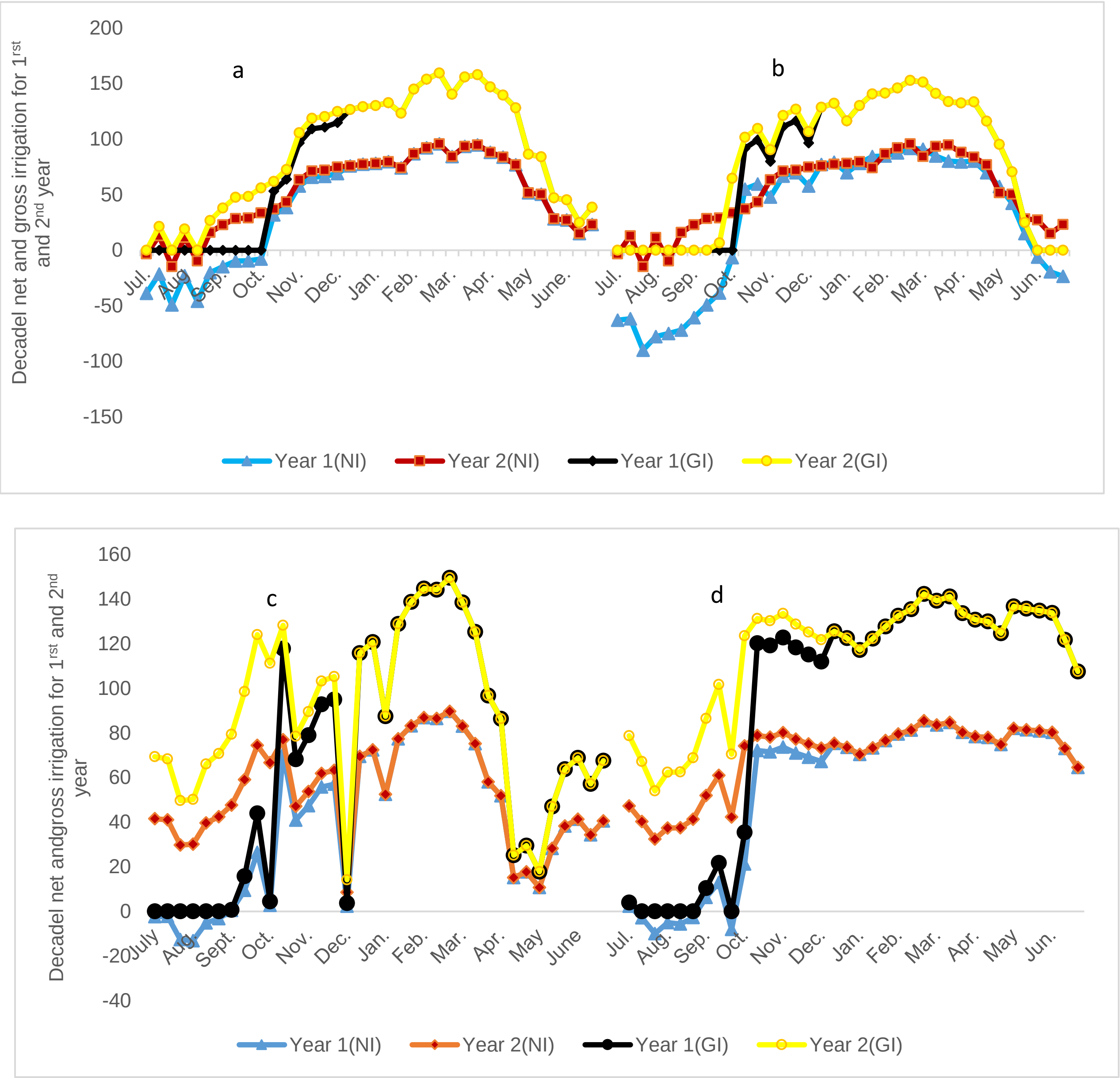


Figure 4: Estimated decadal net and gross irrigation a) Assossa, b) Bako, c) Teppi, and d) Melkassa

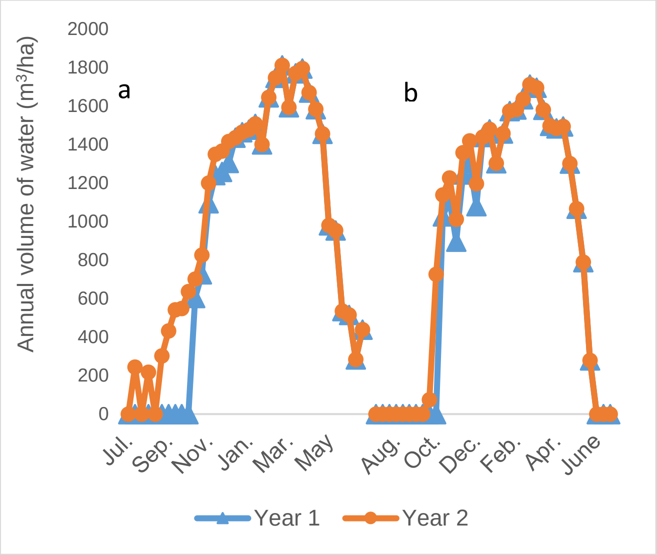
Volume of irrigation

The volume of irrigation water required for banana production in the Assossa was estimated during the dry season from the second decade of October to the first decade of June. The study indicated that Cavendish banana production requires the highest irrigation water per decade in Assossa, specifically from Feb. to March (figure 5a). The total water required during the first year is 32,305.9 m3/ha per year (Table 3). Similarly, 358857.5 m3/ha/year of irrigation water volume is required during the second and subsequent production years.

The annual volume of water required for Cavendish banana production ranges from 1635.6 m3/ha during the dry periods in February, March and April (figure 5b), with a total of 30040.2 m3/ha per year in the first production year in Bako (Table 3). Similarly, a total of 31528.0 m3/ha irrigation water per year during the second and subsequent production years is estimated.

The volume of irrigation water required for banana production in the Teppi area varies from zero during the rainy season to 1698.3 m^3/ha/year on the third of February (Figure 5c). A total of 26981.9 m3/ha/year of irrigation water is needed for banana production during the first year (Table 3). For the second and subsequent years, 26981.9 m^3/ha/year of irrigation water is required.

The estimation of the decadal volume of irrigation water is highest from Feb. to June, reaching a peak of 1603.7 m3/dec (figure 5d) in Melkassa. During the dry months, 38328.6 m3/annum of irrigation water is required to produce one ha of Cavendish banana during the first year (Table 3). At the same time, most elevated a total of 45004.5 m3/ha of irrigation water was recorded per year during the second and subsequent years for banana production.



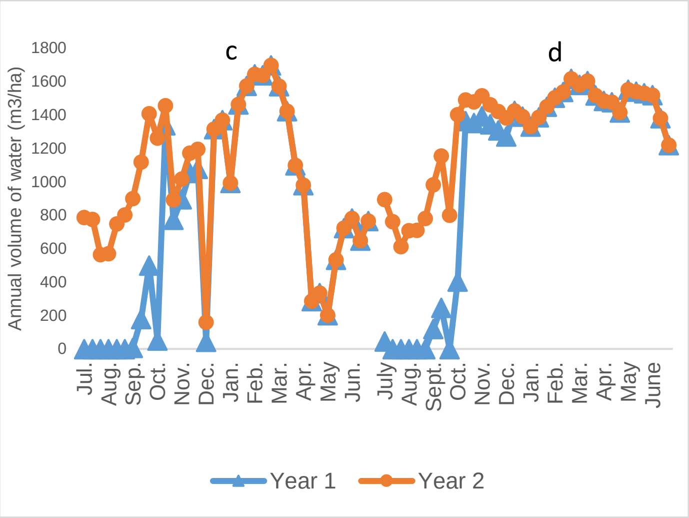


Figure 5: Estimated annual volume of water a) Assossa, b) Bako, c) Teppi, and d) Melkassa

The annual crop water requirement, net irrigation water requirement, gross irrigation, and required volume for banana production varied among the study areas. The first and second years of production also show differences in estimated parameters. Table 3 below shows the summary of estimated parameters on an annual basis. Comparatively, in Melkassa, the production of bananas requires more irrigation water than in other areas. Scholars have also calculated banana crop water and irrigation water requirements. According to Soomro *et al*. (2023), the irrigation and crop water requirements for bananas were 1966.7 mm and 2,012.3 mm, respectively, during the growing season. The total water requirement of bananas is high, ranging from 1200mm in humid tropics to 2200mm in dry tropics. The total water requirement of banana plants is about 900-1200 mm throughout their life cycle (Ghosh *et al*., 2018). Drip irrigation, as discussed by Santosh and Tiwari (2019), can reduce water consumption by 12% for the main crop and 22% for the ratoon crop, particularly when combined with black plastic mulch. The water requirements of banana crops vary depending on climate, soil type, and irrigation method. That is why the estimation of banana water requirements has different values in the study area.

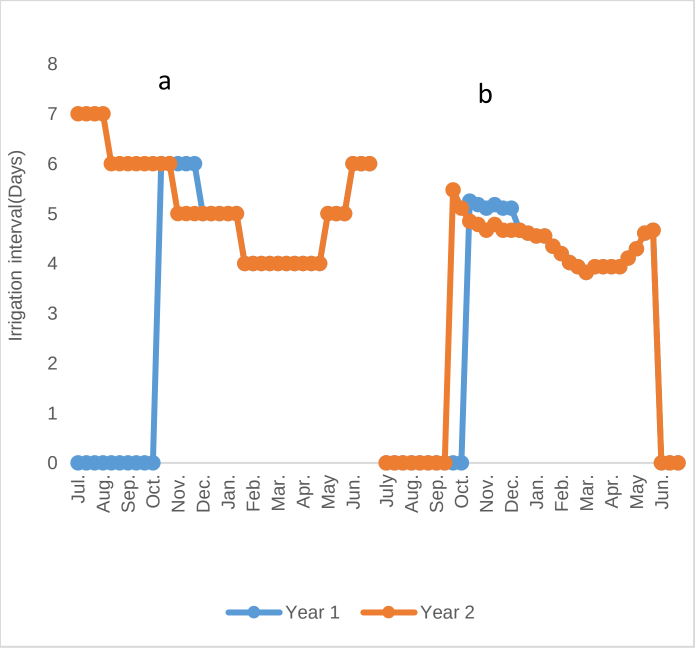
Table 3: The summary of annual calculated parameters for all study areas.

Estimated parameters /Annual	**Study areas**							
	Assossa		**Bako**		**Teppi**		**Melkassa**	
	1st year Prod.	**2nd year Prod.**	**1st year Prod.**	**2nd year Prod**	**1st year Prod.**	**2nd year Prod.**	**1st year Prod.**	**2nd year Prod**
ETc (mm/annual)	2297	2679.3	2425.4	2867.8	2479.4	2988.7	2468.0	2855.0
Pe (mm/year)	813.3	813.3	1458.4	1458.6	1093	1093.0	478	478
NI (mm)	1706.3	1893.9	1609.3	1689.0	1425.1	1895.7	2024.4	2377.8
GI (mm)	2843.8	3156.5	2682.2	2815.0	2375.2	3159.5	3263.7	3951.3
V(m3/ha)	32305	35857	30040.	31528.0	26981.9	35891.9	38328.6	45004.5

Irrigation Intervals

The irrigation interval varies depending on the season's climate and year of production. During the dry months, the interval is around four days, while during the cool and rainy season, it is around six in the first year of production in Assossa. When rainfall is assumed to be sufficient in the rainy months, irrigation is unnecessary, as shown inFigure 6a. During rainy irrigation, the interval reaches up to seven days in Assossa and around four days in the dry season. The estimated irrigation intervals at the Bako area range from 4 to 5 days, depending on the prevailing weather conditions during the first year of production.

In contrast, an estimated four days intervals to six days depending on weather conditions during the second and subsequent production years, as shown in Figure 6b. The estimates of the decadal irrigation interval showed that the irrigation interval ranged from a 0-day interval during the rainy season of July, August, and October to 4 days during other dry months for Teppi (Figure 6c). Similarly, the irrigation intervals range from 2 days during the dry season to four days during the rainy season in the second year of production. The estimation of decadal irrigation intervals showed that the irrigation interval for banana plantations at Melkassa starts from the second decade of October and is every four days throughout the dry months until July for the second year of production, Whereas, during high rainfall periods, an interval reaches 12 days for the first year of production as shown on figure 6d below. This is supported by literature suggesting that bananas' irrigation intervals are 3-4 days during hot periods and 7-8 days during cool weather (www.fao.org/3/s2022e/s2022e02.htm).



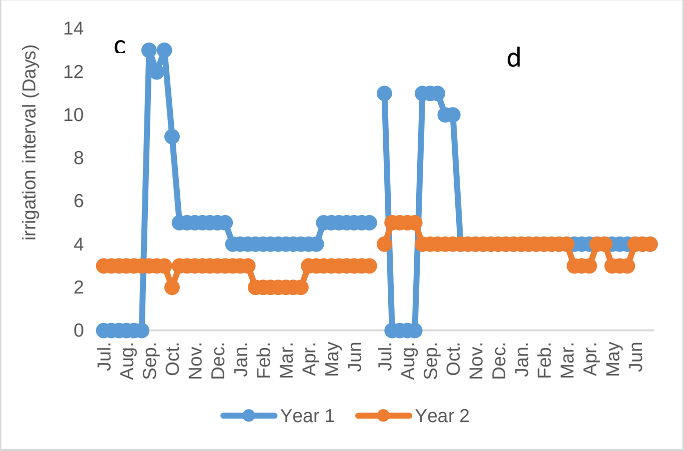


Figure 6: Estimated irrigation interval a) Assossa, b) Bako, c) Teppi, and d) Melkassa

Drainage management and water quality in banana farming

Banana grows in the lowland areas of Ethiopia, where the temperature remains high throughout the year. It requires a significant amount of irrigation water for most of the year. Excess irrigation water from the irrigation supply and rainfall should be immediately drained from the banana field. Flood irrigation in banana farms exacerbates banana root diseases and nematodes. Many large-scale commercial banana farms in Ethiopia, such as Awara Melka, Melka Sedi farms, and others, were abandoned due to various irrigation-related problems (Gebre Mariam, 2003). Reports show that bananas are flood-sensitive species, with rapid tree responses occurring when soils become waterlogged (Schaffer *et al*., 1992). Excess rainwater beyond FC during rainy days and throughout the rainy season should be drained from banana farms. Thus, all banana growers in lowland areas should take care to mitigate the adverse effects of flood irrigation and poorly drained farms, especially where there is a problem with salinity. It is essential to take precautions to prevent further salinity development during irrigation.

CONCLUSIONS AND RECOMMENDATIONS

Applying the right amount of irrigation water to meet banana water requirements conserves water resources, enhances yield and quality, and yields economic benefits. Despite the substantial need for irrigation in banana cultivation, water availability is severely constrained. Therefore, optimizing irrigation is crucial to achieve sustainable water savings and economic gains in banana-producing regions while maintaining environmental sustainability. The study found that banana evapotranspiration (ETc) significantly exceeds annual rainfall in Assossa, Bako, Teppi, and Melkassa. In the first year of banana production, ETc is estimated at 2279.7 mm for Assossa, 2425.4 mm for Bako, 2479.4 mm for Teppi, and 2468.0 mm for Melkassa. In subsequent production years, ETc amounts to 2679.3 mm, 2757.5 mm, 2988.7 mm, and 2848.8 mm, respectively, for these areas. Net irrigation totals 1763.8 mm and 1893.9 mm in

Assossa, 1609.3 mm and 1689 mm in Bako, 1425.1 mm and 1895.7 mm in Teppi, and 2024.4 mm and 2377.0 mm in Melkassa for the first and consecutive production years. Gross irrigation totals 2843.8 mm and 3156.5 mm in Assossa, 2682.2 mm and 2815 mm in Bako, 2375.2 mm and 3159.5 mm in Teppi, and 3263.7 mm and 3961.7 mm in Melkassa for the first and consecutive production years. The study reveals a significant annual irrigation water requirement per hectare for banana production in Ethiopia's study areas.

Consequently, Ethiopian banana growers should implement supplementary irrigation during dry seasons to ensure sustainable production. While relatively simple, ET-based irrigation scheduling offers reasonable estimates of irrigation water needs. Therefore, local weather stations can be utilized by banana growers to estimate ETo (evapotranspiration) and determine daily irrigation requirements until more precise scheduling methods are established.

However, precise irrigation scheduling should consider soil moisture monitoring using appropriate devices and sensors, comparing this data with other scheduling approaches. This is essential for accurately determining daily irrigation requirements for various banana shoots at different growth stages and locations. Further investigations are necessary to quantify water requirements for banana shoots per mat per hectare across production years. Additionally, considering factors such as soil type, crop density, growth stage, tree spacing, rainfall, irrigation efficiency, and water quality is vital in water use calculation and measurement for each method.

Conflict of interest

The authors declare that they have no conflict of interest.

Data Availability

All data generated during the manuscript analysis are included within the article.

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