Sustainable Water Resources Management (2023) 9:187
https://doi.org/10.1007/s40899-023-00976-2

ORIGINAL ARTICLE

Assessment of climate variability impact on water supply sustainability in rural areas of northern Ethiopia

Muruts Getachew[1] · Bizuneh Asfaw Abebe[1] · Berhane Grum[1]

Received: 14 December 2022 / Accepted: 26 October 2023 / Published online: 20 November 2023

Abstract
Climate variability can affect sustainability of water resources in rural areas. The impact of climate variability is greater for areas having low annual rainfall and complex topography. The objective of this study was to investigate spatial and temporal variability of climate and its impact on sustainability of rural water supplies in northern Ethiopia. Station-based climate data of six meteorological stations were gathered from Ethiopian Meteorology Institute (EMI) with varied recorded periods. Rainfall trend analysis was conducted using the Mann–Kendall test and Sen's slope estimator. Rate of water yield for hand-dug wells and springs was measured using pumping and recovery tests. Results of this study showed that no significant trends were detected for annual and seasonal rainfall of all stations, except the summer rainfall of Dengolat station. Average monthly minimum and maximum temperatures in the last 3 decades have been increasing by 0.68 and 0.34 °C, respectively. Yield test results of wells and springs of the study area varied from 0.01 to 1.34 L per second (l/s). Yield test results for wells and springs showed that only 19% of the water supply schemes satisfy the daily domestic consumption of 25 L/capita/day. The study implied that water yield of the water supply schemes is impacted by temporal and spatial climate variability. Water yield of wells and springs was positively correlated with annual rainfall, but negatively correlated with slope gradient of the study area. Water yield of the water supply schemes located nearby to check dams, reservoirs, ponds, and perennial rivers was relatively better compared to others schemes.

Keywords Rainfall and temperature variability · Trend analysis · Water supply sustainability · Well and spring yield rate

Introduction

Water is recognized as a key factor for poverty reduction and economic development. Domestic water supply is one of the basic primary necessities for human beings to live healthy, survive, and be productive. In this study, water supply describes the amount of water produced from wells and springs and supplied to the rural communities. As many of the water supply schemes (WSSs) tested for yield performance had limited yield rates, the schemes were mainly used to fulfil the basic needs of users. In 2022, 2.2 billion people of the world still lacked safely managed drinking water and the projection implies that no region is on track to achieve the universal water access by 2030. A dramatic progress is needed to increase sixfold to meet the sustainable development goal (SDG) global target (WHO, Unicef, World Bank 2022; WHO and UNICEF 2023). Observational records and climate projection indicated that freshwater resources have the potential to be strongly impacted by climate change, and observed warming over several decades has been linked to changes in the large-scale hydrological cycle (Bates et al. 2008). Nowadays, many African countries including Ethiopia are expected to be highly vulnerable to climate variability and future climate changes (Awulachew et al. 2007; Conway and Schipper 2011; MoWIE 2016; MoWIE 2018; MacAllister et al. 2020; Abebe et al. 2022). It is, however, difficult to adequately model the impact of climate change on hydrological systems because of the complex interaction of climate and hydrological processes. As a result, it is very difficult to predict the likely impacts of climate change on rural water supply schemes (Bonsor et al. 2011; Taylor et al.

✉ Bizuneh Asfaw Abebe
bizuneh1997@gmail.com

Muruts Getachew
murget521@gmail.com

Berhane Grum
berhanegr@gmail.com

[1] School of Civil Engineering, Mekelle University, P. O. Box 231, Mekelle, Ethiopia

2013). In fact, perceptions and experience of many African rural communities showed a frequent and extended droughts which relate with climate variability and changes (Meze-Hausken 2004; Nyahunda and Tirivangasi 2019; MacAllister et al. 2020).

Although climate variability and change will unquestionably be vital in determining future water security, other drivers, such as population growth, economic development, technical and social determinant, and rising food demands, are likely to provide greater pressure on rural water supplies (Wang et al. 2016; Esayas et al. 2019; Twisa and Buchroithner 2019). Similarly, WHO (2009) stated that climate variability is becoming a threat to water supply and sanitation. Thus, the ever-increasing water demand in sub-Saharan Africa will depend on development of groundwater resources (MacDonald et al. 2012). Water availability from surface water sources or shallow groundwater wells depends on the seasonality and inter-annual variability of either rainfall or combination of rainfall and streamflow (Kahsay et al. 2017; Kotchoni et al. 2018). Globally, ground water is the source of 36% of all domestic water demands (Bonsor et al. 2011; Taylor et al. 2013). The situation is not different in Ethiopia, where the majority of rural water supplies are groundwater-based despite Ethiopia having 12 river basins and 20 lakes with 122 billion m^3 annual runoff (Awulachew et al. 2007).

Most rural communities in Africa rely on unimproved sources, such as open water and shallow wells (Bonsor et al. 2011). Water springs (SPs) and hand-dug wells (HDWs) are the major sources of domestic and irrigation water for the vast developing countries as a result of relatively low construction and maintenance costs (Ibrahim et al. 2021). For example, in Ethiopia, the main domestic water sources for rural population (more than 80%) are SPs, HDWs, shallow and deep wells, rivers, and ponds. Nearly 23.3% of the Ethiopian population is dependent on unimproved sources, such as rivers, ponds, unprotected SPs, and open HDWs (MoWIE 2016).

Variability of water availability, overexploitation, technical determinant, and climatic effects exacerbate the limitation to access and sustainability of water supply in rural areas (Twisa and Buchroithner 2019). In northern Ethiopia, the presence of climate variability highly affects the availability of water resources (Gebrehiwot and van der Veen 2013; Hadgu et al. 2013). Climate change is likely to modify groundwater recharge patterns, though groundwater recharge is thought to be a function of climatic factors, topography, local geological formation, and land-use/land-cover (LULC) types (Dragoni and Sukhija 2008; Sethi et al. 2020; Alem et al. 2022). Moreover, rainfall variability and evaporation are responsible to shifts in soil moisture deficits and surface water runoff, and expected to have an effect on groundwater recharge (Kahsay et al. 2017).

According to FAO (1984), 50% of the African mountains with elevation above 2000 m are found in Ethiopia. It is reported that mountains can contribute more water to downstream users (Wangdi et al. 2017). However, water supply users who settle in mountainous areas are likely to be affected by scarcity of water due to minimum groundwater recharge (Walraevens et al. 2009). Thus, domestic water sources in the northern Ethiopian highlands are influenced by the rugged topography and degraded land which limit infiltration and water holding capacity of the ground.

About 80% of people living in rural areas are still lacking at least basic drinking water services in 2022, and the coverage gap between urban and rural is the greatest in sub-Saharan Africa (38%) and in Latin America and the Caribbean (27%) (WHO and UNICEF 2023). Ethiopia has made remarkable progress in water supply development and access over the last 2 decades (Calow et al. 2015). According to UNICEF and WHO (2015), Ethiopia has reached a water supply coverage of 57% (48.6% in rural and 93% in urban areas) in 2015. Similarly, MoWIE (2015) reported that rural, urban, and overall water supply coverage of Ethiopia in 2014 was estimated to be 75.5, 84.1, and 76.7% respectively. In Tigray, where this study is located, water supply coverage was reported to be 58% (TBoWR 2019). However, with the current pressing issues of climate variability, sustaining rural water supply systems and services remains a huge challenge. According to MacAllister et al. (2020), average non-functionality rate out of 5196 sampled WSSs in Ethiopia was 25% for hand pumps and 40% for motorised boreholes. Similarly, MoWIE (2018) identified that the main challenges of water supply system are significant gap in the adequacy of water supply system versus demand; reliability, and quality of water sources; and climate conditions including frequent droughts.

According Bates et al. (2008), it is highly complex to know the relationship between rainfall, river flow, and contamination of the water supply. Many water supply utilities around the world face challenges due to population growth and climate change (Kiyan et al. 2023; Talema 2023). The quality indicator parameters and pollution of water depends on human activities, population, temperature, rainfall intensity, degree of flow, salinity, source of water, industries, waste water availability, and others (Bates et al. 2008; Talema 2023). Two-thirds of people in sub-Saharan Africa and one-third of people in Central and Southern Asia still rely on unsafe drinking water (WHO, Unicef, World Bank 2022). Over 85% of improved rural water sources of Ethiopia were reported as contaminated (World Bank 2017). As availability of industries and other oily factories in the study area was less the main sources for pollution may be due to natural hardness (for 68% of the people), fluoride, and domestic waste (CSA 2017).

In semi-arid areas, despite the frequent drought, unreliable rainy seasons, concentration of annual rainfall on certain days of months, there is lack of detail scientific studies, data and organized solutions for domestic water supply related problems. The main objectives of this study were, therefore to analyze temporal and spatial climate variability, measure water yield of wells and springs, and assess the impact of temporal and spatial climate variability on sustainability of rural WSSs in Tigray region, northern Ethiopia.

Materials and methods

Description of the study area

The study area is found in the south-eastern zone of Tigray regional state, northern Ethiopia. Geographically, it is located between 12°53′2″ and 13°38′44″N and 39°16′43″-39°52′40″E (Fig. 1). The study area comprises two rural districts or woredas of the south-eastern zone, namely Enderta and Hintalo-Wejerat. Enderta is one of the four woredas of the south-eastern zone and it surrounds Mekelle city, the capital of Tigray regional state. Hintalo-Wejerat has a complex topography and is located south of Enderta woreda (Fig. 1). The study area has 38 Kebelles (sub-administrative units of the woreda) and has a total area of 3151 square kilometers. According to CSA (2013), the population size of the two woredas in 2014 was 300,000 with average population growth rate of 2.5%, out of which 94% are rural inhabitants. Average population density of the study area is about 95 people per square kilometer.

Enderta and Hintalo-Wejerat are part of the rugged and undulating topography of the northern Ethiopian highlands. The landscape is characterized by mountains, plateaus, valley floors, and gorges. The altitude of the two woredas ranges between 1193 and 3537 m above sea level. There is no a separate study that shows detail water resource potential of the study area and the region; however, annual average runoff volume and groundwater potential of Ethiopia are about 122 and 20 billion m^3, respectively, which amounts to per capita water availability of about 1100 m^3 per year (Awulachew et al. 2007). The study area has a semi-arid climatic condition with an extended dry period of 9–10 months. The average effective rainy days (greater than 1 mm) of the study area varies from 40 to 60 per year. The long-term annual average rainfall of the study area is 604 mm in Mekelle (M), 505 mm in Adigudom (A), 720 mm in Dengolat (D), 565 mm in Adishehu (As), 464 mm in Hiwane (H), and 539 mm in Debub (Db) (Fig. 1). The rainfall pattern is predominantly uni-modal type. In general, three distinct seasons can be recognized. The first is the main rainy monsoon season which lasts from June to September; the second is the dry winter season from October to February. The third season is spring from March to May, with occasional showers of rain (15–20% of annual rainfall) is the hottest season of the year.

Data collection and methodological framework

Primary data were collected in the months of April to June in 2017. Similarly, secondary data were collected in the months of January to March in 2017.

Primary data collection involved field measurements, surveying, and interviewing water users. The collected primary data include yield rates of wells and SPs, depth and overall dimensions of wells and SPs, number of users in each scheme, amount of water used per household, and the topographic and land-use conditions of the surrounding area where schemes are located.

Secondary data in this study consisted of rainfall, temperature, and detail information on WSSs. Secondary data were mainly gathered from the Ethiopian Meteorology Institute (EMI) and Tigray Bureau of Water Resources (TBoWR).

The overall methodological framework of this research is demonstrated in Fig. 2.

Water supply scheme data sampling

The study was conducted using a cross-sectional survey approach where data were collected from a representative sample. In this study, purposive type of sampling technique was used to select the scheme types for investigation. Only functional HDWs and SPs were picked for detail evaluation and analysis due to ease of access and minimization of risk of failure during data collection. The dry WSSs were, however, included in the overall climate variability analysis.

The sampling was dependent on the availability of required data from the construction till field study period. HDWs were selected for sampling if they had recorded data of water yield rate during construction or rehabilitation, water depth, and static water levels. SPs were prioritized for sampling if they had recorded water yield rate and did not have seepage problem. Moreover, the sampled HDWs and SPs had a known construction time. Around 1136 WSSs were constructed in the two Woredas untill March 2017. Out of the 1136 WSSs, 425 were HDWs, 164 were SPs, 533 were shallow wells, and 14 were deep wells.

Based on the selection criteria, 65 HDWs and 106 SPs satisfy the requirements and were prioritized for field sampling. During field work, only 30 HDWs and 22 SPs were functional and they fulfil the criteria for water yield test. However, only 21 HDWs were accessible and not difficult to open their manholes. Moreover, all the 22 SPs were chosen for detail analysis. All the dried WSSs ($n = 79$), which covers 29% of the total non-functional schemes, were also selected for analysis. Furthermore, questionnaire was prepared and

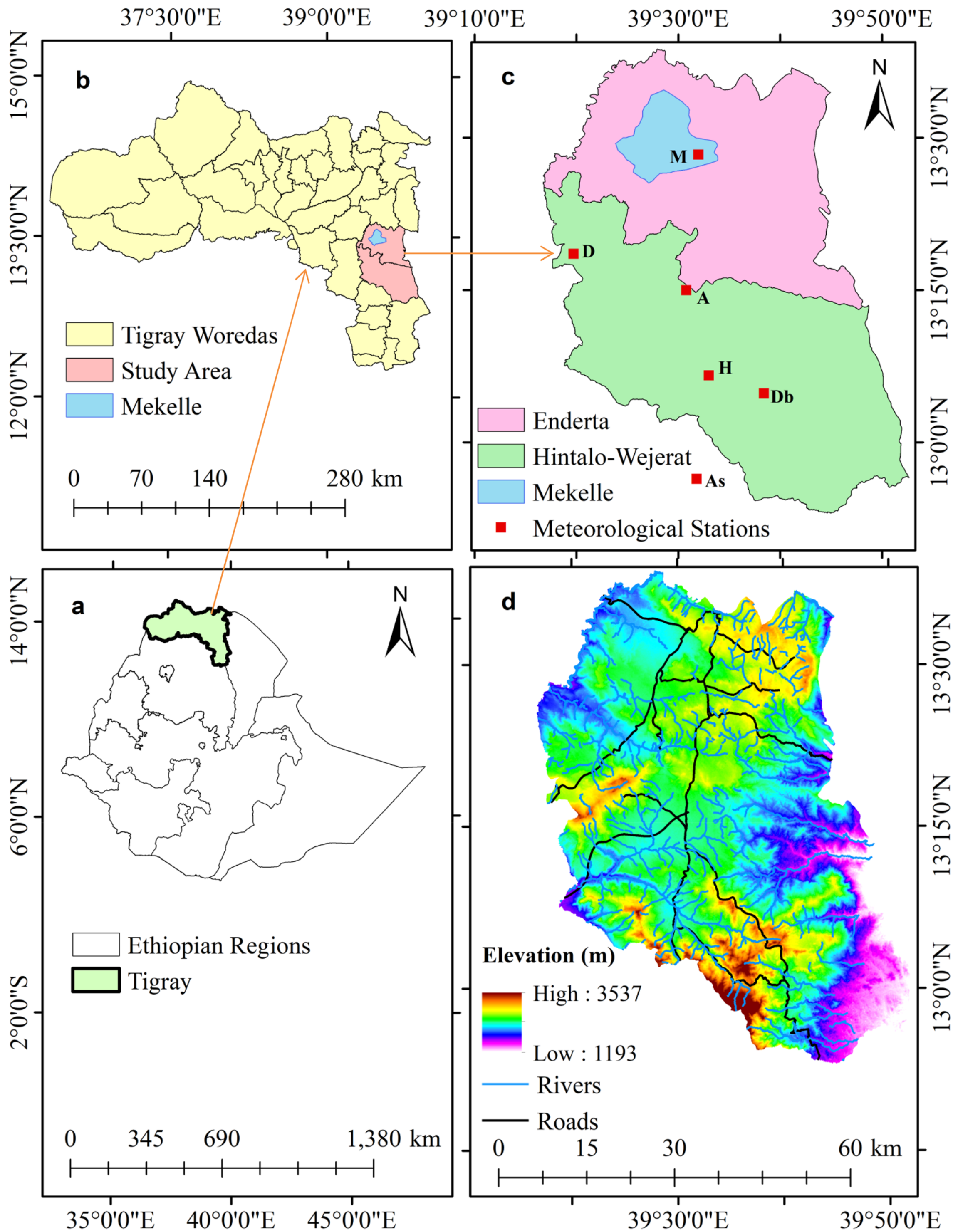

Fig. 1 **a** Geographical locations of Ethiopia and the study area. **b** Administrative woredas of Tigray region. **c** Existing meteorological stations. **d** Elevation. **e** Terrain slopes. **f** Land-use/land-cover (LULC) map of the study area

distributed to target groups to assess the level of satisfaction of the users. The questionnaire survey was aimed at collecting data about the satisfaction and situations of selected WSSs for the years 2015 to 2017.

Most of the functional SPs tested for their performances are found in the rugged topography of the study area. The water supply sources are located in different LULC types. The LULC of a certain water supply source was represented

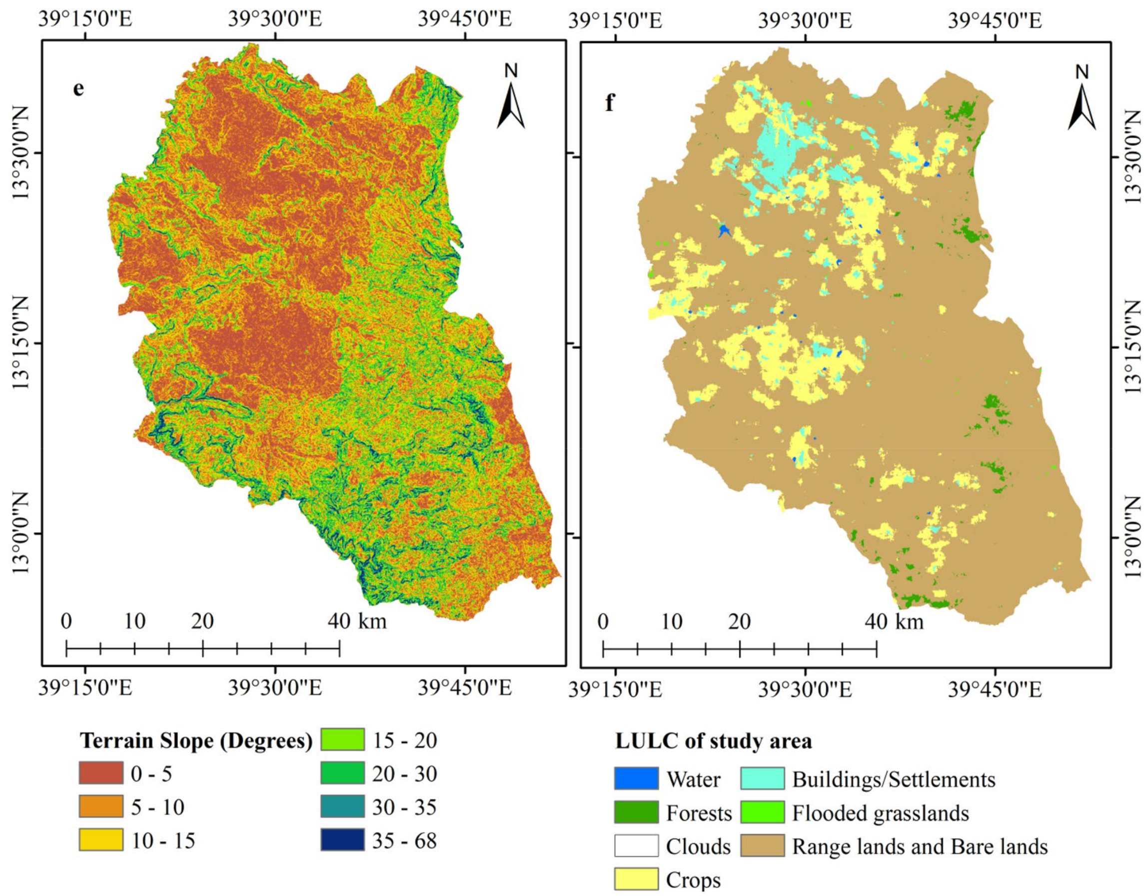

Fig. 1 (continued)

by the dominant LULC of nearby areas. In most cases, the dried WSSs were located in grazing land, bare land, and cultivated lands. More than 72% of dry wells were found in slope gradients greater than 4%; and 25% were located in gradients greater than 8%. Figure 3a, b indicates the location and distribution of functional HDWs and SPs, dry WSSs, and spatial distribution of annual rainfall.

Measurement of water yield and static water level

Water yield of the WSSs was measured using a pumping and recovery tests (Amah and Anam 2016; Balasubramanian 2017). Pumping test is a practical and reliable method of estimating the performance and yield of wells (Balasubramanian 2017). The duration of pumping test could vary from hours to days. The pumping test for surface or submersible pump installation needs great care and long pumping duration, which may be more than one day (Gross 2008). In this study, duration of pumping test for the HDWs varied from 1 to 3 h, depending on the potential of the wells. Duration of recovery for the pumped wells also varied from 1 to 11 h.

The static and recovery water levels were measured using a dip meter. The dip meter has an electric sensor that displays light with an immediate sound when the sensor reaches or touches the surface of water. This instrument was also used to know water level at different time during the pumping test and recovery of wells, and water level change of SPs. Figure 4 shows the procedures for measuring water yield and static water level of the wells. The yields of the SPs with gate valves were computed by measuring the internal dimensions of the temporary reservoirs and change in water level during observation by dip meter. For SPs without gate valves, yield was measured using a bucket method.

Meteorological data analysis

Meteorological data records such as rainfall and temperature were obtained from EMI. The description of the meteorological stations in the study area is summarized in Table 1. Consistency of the rainfall data was checked by the double mass curve method (e.g., Gao et al. 2017). Homogeneity of the meteorological data record was checked by analyzing the

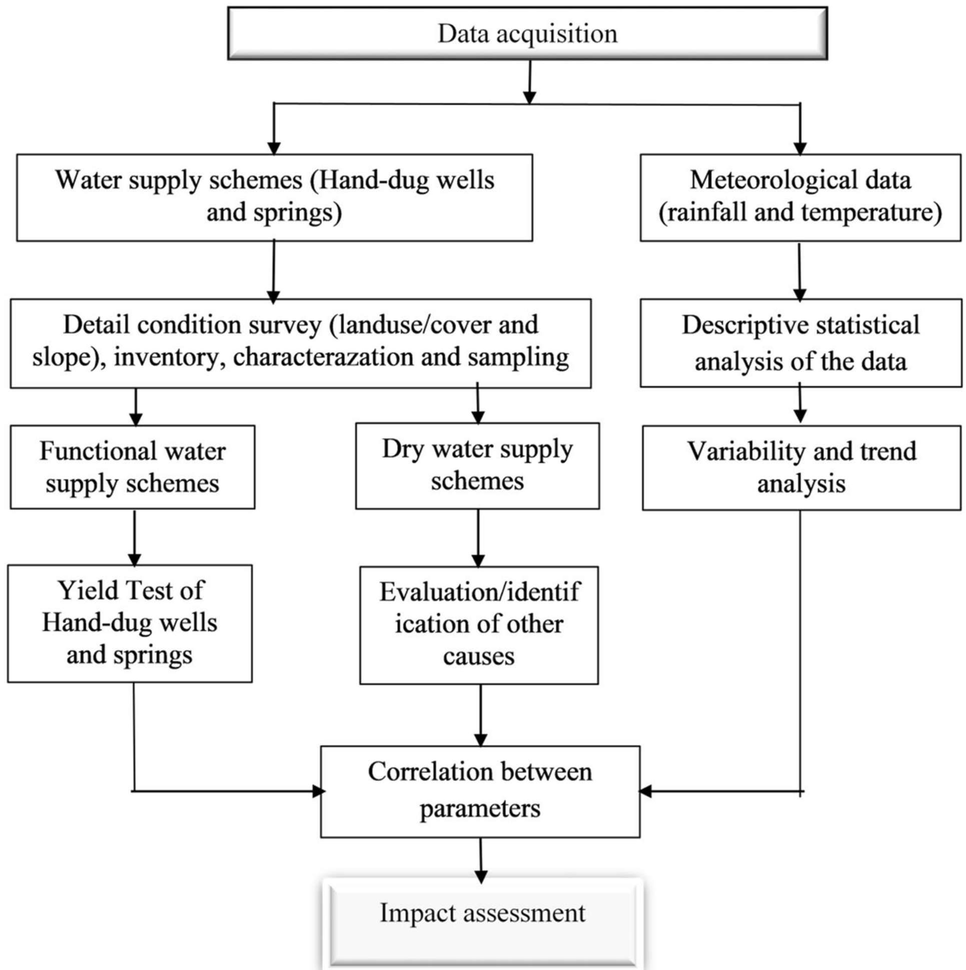

Fig. 2 Overall conceptual framework of the research work

deviation of a record from the mean as described in Buishand (1982).

Based on the length of recorded years of meteorological stations, Thiessen polygon was used to generate areal rainfall of the study area before 2008 (only Mekelle, Adigudom, Dengolat, and Adishehu stations were considered) and after 2008 (all stations). The generated areal rainfall was used to correlate rainfall with measured water yields and dried WSSs.

Rainfall and temperature variability

A standardized rainfall anomaly (SRA), precipitation concentration index (PCI), and coefficient of variation (CV) were used for analyzing rainfall variability (Bewket and Conway 2007; Gebrehiwot and van der Veen 2013; Hadgu et al. 2013) of the study area. SRA was calculated as the difference between annual rainfall of a particular year and the long-term average rainfall records divided by the standard deviation of the long-term data. SRA was used to evaluate inter-annual fluctuations and examine the nature of trends of rainfall throughout years (Eq. 1)

$$\mathrm{SRA} = \frac{P_i - \mu}{\mu}, \qquad (1)$$

where SRA is standardized rainfall anomaly; P_i is annual rainfall of a particular year; μ is mean annual rainfall for the period of observation.

PCI was used to evaluate the distribution of the rainfall throughout the months of the year using the method used by De Luís et al. 1999), which is the modified version of Oliver's (1980). The PCI was computed using Eq. (2)

$$\mathrm{PCI} = \left(\sum_{i=1}^{12} P_i^2 / (\sum_{i=1}^{12} P_i)^2 \right) * 100, \qquad (2)$$

where *PCI* is precipitation concentration index and P_i is the rainfall amount of the *i*th month. According to Ngongondo et al. (2011) and Oliver (1980), PCI values of less than 10 indicate uniform monthly distribution of rainfall, values between 11 and 20 indicate high concentration, and values

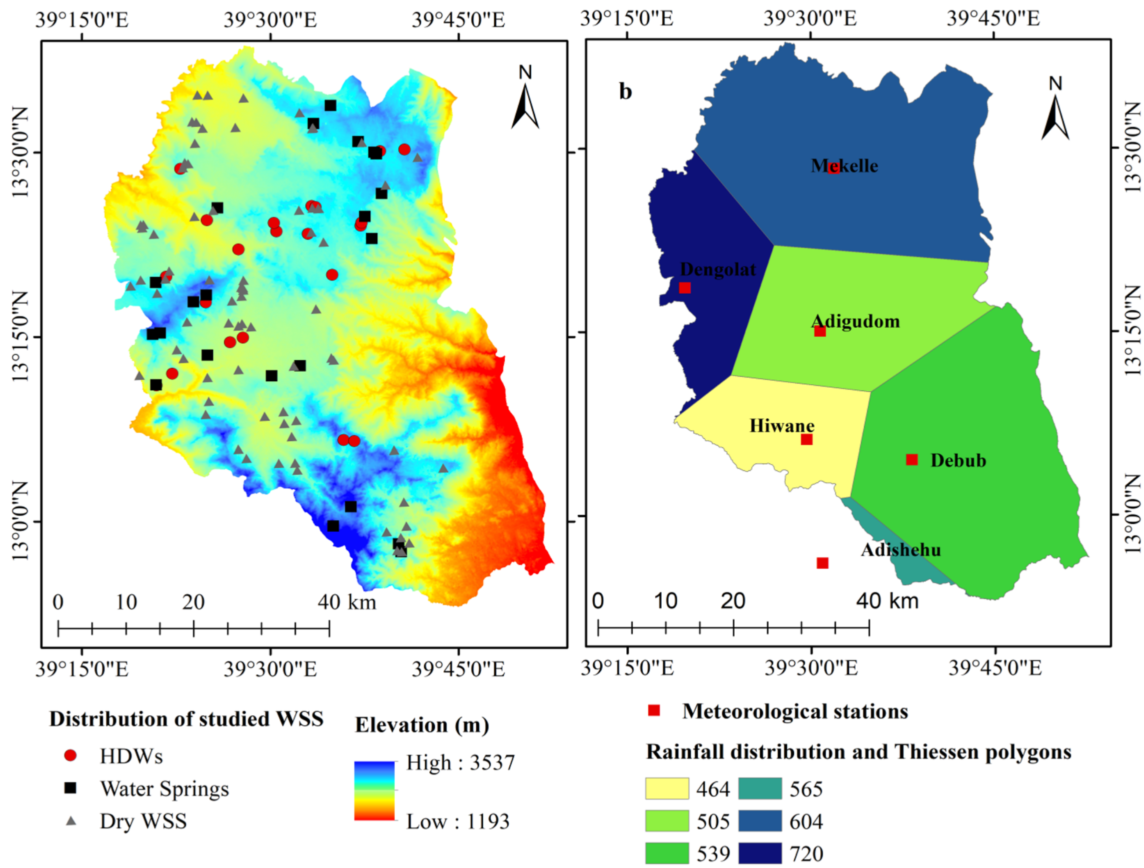

Fig. 3 Location of water supply schemes (WSSs) and rainfall distribution in the study area: **a** distribution of studied WSSs (hand-dug wells (HDWs), springs and dry WSSs); **b** areal rainfall distribution estimated using Thiessen polygon method

above 21 indicate very high concentration of monthly rainfall distribution.

The inter-annual and seasonal rainfall variability was determined by CV, which is obtained by dividing the standard deviation of the event to the long-term average rainfall for the given period of each weather station (Eq. 3). Similarly, temperature variability was expressed in monthly, yearly, and decadal variations of the observed temperature in Mekelle Airport. The CV quantifies the overall variability of rainfall records of an area. Based on the CV values (Addisu et al. 2015), rainfall variability is categorized into low ($CV < 20$), moderate ($20 < CV < 30$), and high ($CV > 30$)

$$CV = \frac{SD}{\mu} * 100, \quad (3)$$

where CV is coefficient of variability; SD is standard deviation; $\boldsymbol{\mu}$ is long-term mean value

Rainfall and temperature trends

Trend analysis of rainfall and temperature was conducted using the Mann–Kendall test (Salmi et al. 2002; Yue and Wang 2004; Mavromatis and Stathis 2011). The Mann–Kendall test is a statistical non-parametric test which is widely used for analyzing trends of hydro-meteorological time-series (Kumar et al. 2010; Mavromatis and Stathis 2011; Abrha and Simhadri 2015; Abebe et al. 2022). The advantage of the Mann–Kendall test for trend analysis is that it has low sensitivity to rushed disruptions due to inhomogeneous data (Tabari et al. 2011; Abebe et al. 2022) and the data should not have to be normally distributed.

The slope of statistically significant trends in rainfall and temperature records was estimated using the Sen's slope estimator (Sen 1968). The Sen's slope estimator can be applied if the trend of the time-series data is linear.

Correlation with water yield of wells and springs

Precipitation and temperature are the two major sensitive parameters that govern hydrologic change (Conway and

Fig. 4 Measurement procedure for water yield and static water level of hand-dug wells: **a** digging manhole, **b** measuring water level, **c** measuring diameter of the well, and **d** pumping water

Table 1 Description of meteorological stations in the study area

Meteorological station	Northing	Easting	Altitude (m.a.s.l)	Recorded data	No. of years	Available data type
Mekelle	13.47°	39.53°	2248	1960	57	Daily rainfall, minimum and maximum temperature
Adigudom	13.25°	39.53°	2104	1972	45	Daily rainfall
Dengolat	13.31°	39.32°	2070	1995	22	Daily rainfall
Adishehu	12.94°	39.53°	2465	1997	20	Daily rainfall
Hiwane	13.11°	39.55°	2050	2008	9	Daily rainfall
Debub	13.08°	39.64°	2080	2009	8	Daily rainfall

Schipper 2011). Correlation is a statistic used to strengthen the validity and reliability of the evidence by knowing the relationship between two variables (Landau and Everitt 2004). To know the relationship and impact of rainfall and slope of surrounding area on water yield of water wells and SPs, Pearson correlation was used at 5% significant level.

Results and discussion

Rainfall variability

The long-term average annual rainfall distribution of the study area varied from 464 mm in Hiwane to 720 mm in Dengolat. In almost all stations, the rainfall character is unimodal type. Annual rainfall in all stations is mainly concentrated in the summer season (June–September). The contribution of summer rainfall to the annual total ranged from 74.3% in Debub to nearly 89% in Adigudom and Adishehu (Table 2). Spring rainfall makes a considerable contribution to the annual total in Debub (20%), Dengolat and Mekelle (16%), and Hiwane (15%). Annual rainfall of each station of the study area highly concentrates on July and August, from 62% in Debub to 73% in Adigudom, as shown in Table 2.

The above results are similar with previous studies in the region (Bewket and Conway 2007; Abebe et al. 2022).

Average monthly rainfall amount of the stations highly varies throughout the year, as shown in Fig. 5. The minimum average monthly rainfall varies from 0 mm (January and December) to 164 mm (August). The maximum average monthly rainfall varies from 5 to 251 mm in the similar months.

The CV of stations for summer season showed that rainfall in the study area has high inter-annual variability (Table 3). Annual rainfall variability was high and CV varied from 19% in Dengolat to 41% in Adigudom. Generally, the spring and the winter rainfalls are much more variable than the rainfall of the summer season. Moreover, the summer rainfalls varied from a CV of 22% for Dengolat to 46% for Adigudom. The seasonal and annual rainfall variability analysis results of Hadgu et al. (2013) and Gebrehiwot and van der Veen (2013) were similar with the findings of this study. In contrast, a study in a nearby region to this study area by Bewket and Conway (2007) stated that the summer rainfall distribution had moderate inter-annual variability.

The spring rainfall for the study area showed high inter-annual variability (CV > 52% in Debub and 121% in Dengolat). Similarly, inter-annual variability for Hiwane was 34%. This result is in agreement with previous studies in Ethiopia

Table 2 Annual and seasonal rainfall distribution and concentration of rainy times

Stations	Summer rainfall (mm)	Spring rainfall (mm)	July contribution	August contribution
Mekelle	489 (81%)	96 (16%)	33%	37%
Adigudom	450 (89%)	47 (9%)	30%	43%
Dengolat	579 (80%)	117 (16%)	30%	35%
Adishehu	498 (89%)	48 (9%)	34%	38%
Hiwane	373 (80%)	71 (15%)	30%	35%
Debub	401 (74%)	106 (20%)	26%	36%

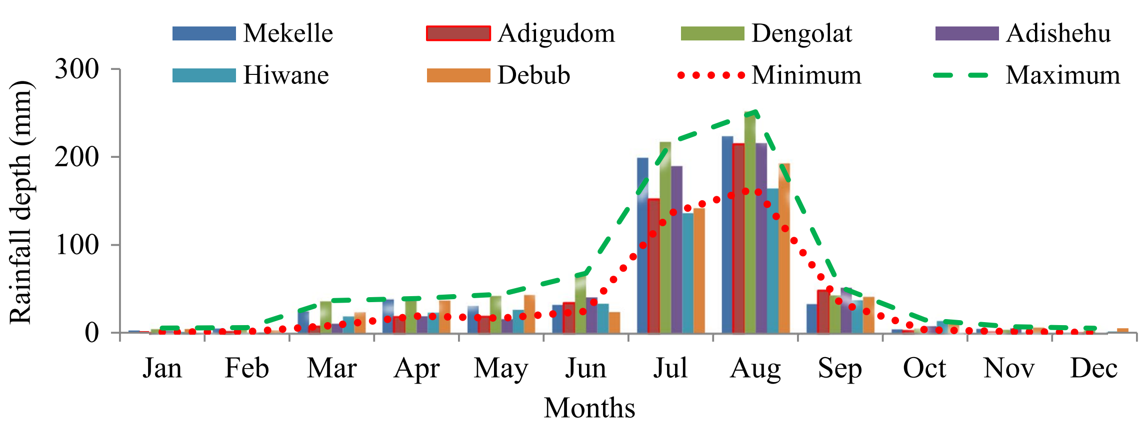

Fig. 5 Average monthly rainfall amount and minimum and maximum ranges

Table 3 Precipitation concentration index (PCI) and the coefficient of variation (CV) of rainfall in Enderta and Hintalo-Wejerat

Station	Overall record					1997–2016				
	Coefficient of variation, CV (%)				PCI (%)	Coefficient of variation, CV (%)				PCI (%)
	Annual	Summer	Spring	Winter		Annual	Summer	Spring	Winter	
Mekelle	26	29	62	98	29	27	29	6	88	31
Adigudom	41	45	76	168	32	0.40	44	84	170	35
Dengolat	19	22	121	126	28	19	20	118	106	28
Adishehu	37	41	81	156	31	37	41	81	156	31
Hiwane	23	24	34	113	26	na	na	na	na	na
Debub	24	30	52	072	23	na	na	na	na	na

na Not available data in 1997

which indicated that the spring rainfall is more variable than the summer season (Seleshi and Zanke 2004; Bewket and Conway 2007; Gebrehiwot and van der Veen 2013). In contrast, in the central highlands of Ethiopia, Rosell (2011) found higher rainfall variability during the summer season. The difference in rainfall variability between the northern and central parts of Ethiopia indicates that there is a large spatial and temporal variation in climate across the country. Seleshi and Zanke (2004) noted that the summer rainfall is impacted by the sea surface temperature over the equatorial Eastern Pacific Ocean. The summer rainfall season over the central highlands of Ethiopia was mainly related to equatorial pacific sea-level pressure, the Southern oscillation index, and the sea surface temperature.

The results for Mekelle station indicate that CV of annual rainfall for the first 3 decades (1967–1996) was 24%. In the recent 2 decades (1997–2016), the CV value of Mekelle station slightly increased to 27%. All stations have PCI values which varied from 23 to 32%. Based on De Luís et al.'s (1999) definition, all stations were grouped under a range of very high concentration of monthly rainfall. The analysis for decadal trend of the PCI value in Adigudom and Mekelle stations indicates that PCI is increasing in every decade. Considering the very high and continuous concentrated rainfall distribution on few months is in agreement with the study by Viste et al. (2012) and Abebe et al. (2022). Based on this result, the availability and sustainability of surface and sub-surface water for drinking and other purposes can then be affected.

The temporal rainfall analysis indicated that rainfall pattern of the study area showed a very high variability throughout year and it is quite often with negative and positive anomalies. A period of positive anomaly with respect to the long-term mean is considered as normal, whereas a period of negative rainfall deviation is noticed as drought condition. In the first 15 years, the deviations from long-term annual rainfall were very low and 67% of the two (Mekelle Airport and Adigudom) stations showed positive anomalies (Fig. 6). However, it is apparent that the period of 2002–2016 has shown 60 and 67% reduction in rainfall at Mekelle Airport and Adigudom stations, respectively.

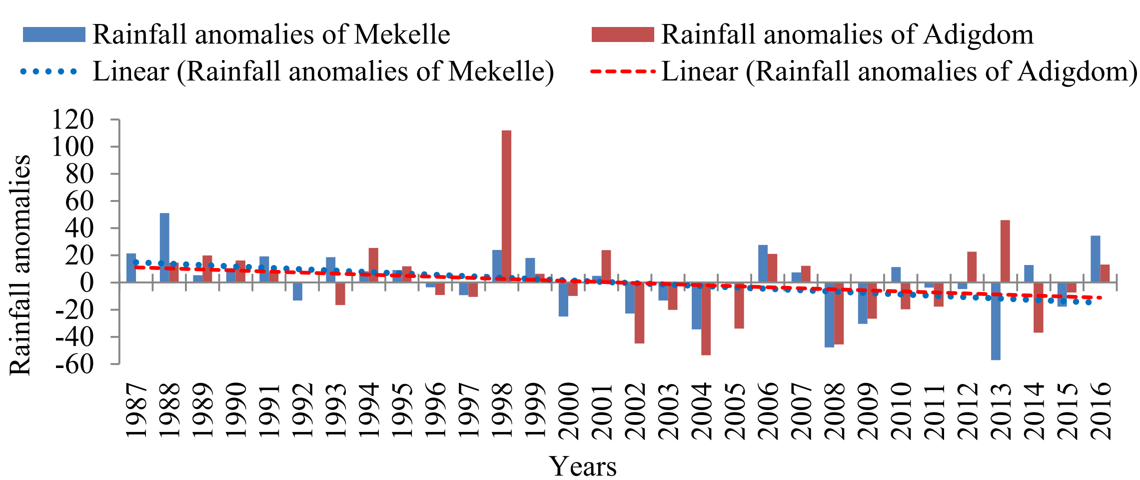

Fig. 6 Rainfall anomalies of Mekelle Airport and Adigudom stations (1987–2016)

Temperature variability

Mean annual temperature distribution in the study area varied from 16.1 to 19 °C for the years 1960 to 2016. Almost 90% of the Tigray region is categorized under semi-arid zones of the country which experience mean annual rainfall of between 300 and 800 mm and a mean annual evapotranspiration of 1600 and 2100 mm (MoWIE 2018). The results of the past 3 decades showed that the average annual maximum temperature for the study area has been increasing by about 0.34 °C per decade, while the average annual minimum temperature has been increasing by about 0.68 ºC per decade. Another study by Gebrehiwot and van der Veen (2013) in different parts of Tigray region has reported similar changes in temperature.

National study revealed that average annual minimum and maximum temperatures of Ethiopia have increased by 0.25 and 0.10 °C, respectively (NMA 2001). This shows that this study area is warming faster than the national average. The minimum temperature is increasing faster than maximum temperature, which implies that warming nights is increasing over the years. Some studies indicated that the magnitude of temperature increase in most parts of Ethiopia is variable (Conway and Schipper 2011; IPCC 2013). The average temperature rises in Africa (0.5 °C per decade), which is similar with the result of study area is faster than the global average and it is expected to occur in future in similar manner (Collier et al. 2008). Generally, the analysis showed that temperature is highly increasing and this could increase the rate of water loss from earth's surface and water bodies.

The analysis on the inter-annual variability within the last 3 decades of monthly average minimum and maximum temperature showed that minimum temperature is the highest in May. The result shows that the fluctuation of the highest monthly average minimum temperature becomes greater in the previous decade (2007–2016) than others. The percentage occurrence of lowest records of monthly average minimum temperature was similar in Januarys and Decembers with some fluctuations. The maximum temperature in the study area is the highest in May and the lowest occurs in August. The mean of the minimum and maximum temperature is 11.6 and 26.1 °C, respectively (Fig. 7).

Generally, temperature of the Mekelle meteorological station is increasing. Average minimum temperature is fluctuating in all months of years for the past 3 decades, 1987–2016 (Fig. 8a). Similarly, the average maximum temperature is increasing in all months of the 3 decades with increasing trends (Fig. 8b).

Trend analyses of rainfall and temperature

Rainfall trend analysis

Average annual rainfall of each station varied both in time and space, but the percentage of the summer's annual rainfall distribution was similar in all stations. Generally, the trend analysis for annual rainfall of all six stations has shown no significant trend at 95 and 99% confidence levels. The trend for Mekelle Airport station for 30-year data series was similar with the results of long-term values. Hiwane has positive but non-significant trend. Debub and Adishehu stations recorded negative trends of annual rainfall. The negative trend is higher for the southern and south-eastern mountainous area of the study area. Table 4 shows the slopes of annual rainfall trends of the study area.

The result of summer (rainy season) trend indicated that Dengolat has positive and significant rainfall trend. Other stations, however, showed a decreasing non-significant

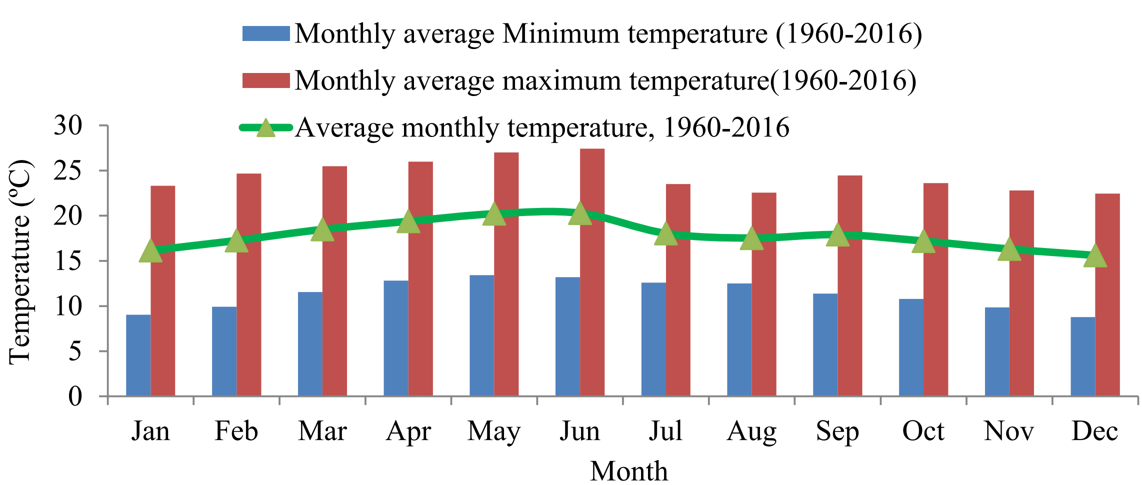

Fig. 7 Inter-annual variability of average, monthly minimum, and maximum temperature in the study area (1960–2016)

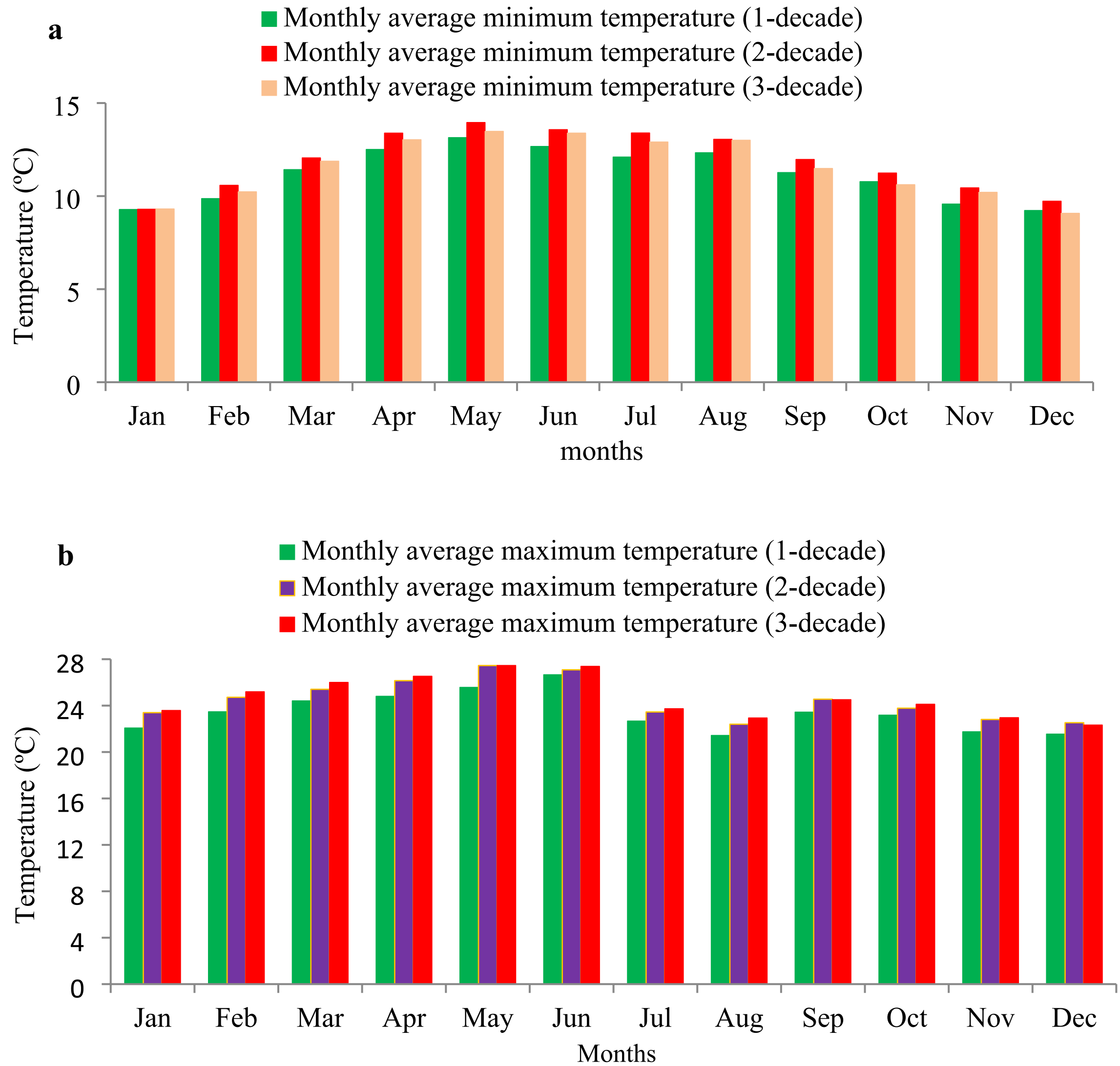

Fig. 8 Inter–annual variability of temperature: **a** monthly average minimum and **b** monthly average maximum for three decades

Table 4 Annual rainfall trends of the meteorological stations

Stations	Record years	Annual		Summer		Spring	
		Sen's slope	Mann–K	Sen's slope	Mann–K	Sen's slope	Mann–K
Mekelle	57	-0.99^{ns}	−0.081	-0.66^{ns}	−0.091	-0.19^{ns}	−0.046
Adigudom	30	-1.65^{ns}	−0.054	-0.97^{ns}	−0.027	-0.23^{ns}	−0.072
Dengolat	22	-1.51^{ns}	−0.48	7.89*	0.255	-1.67^{ns}	−0.117
Adishehu	20	-14.6^{ns}	−0.189	-8.82^{ns}	−0.147	-0.84^{ns}	−0.10
Hiwane	9	0.33^{ns}	0	-16.55^{ns}	−0.22	-0.1^{ns}	−0.056
Debub	8	-36.9^{ns}	−0.286	-17.44^{ns}	−0.36	6.3^{ns}	0.43

Slope = the change rainfall (mm)/year; Mann k = Mann–Kendall trend test, ns = non-significant trend

*Significant trend at 0.05 significant level

rainfall trend. The magnitude of decreasing rainfall trend is higher for Debub, Hiwane and Adishehu. In similar manner, the monthly trend indicated that August and September for Dengolat have positive and significant trends. However, the rest all months of were non-significant for all stations, as shown in Table 5.

Table 5 Monthly rainfall trends of meteorological stations

Stations	Sen's slope											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Mekelle	0	0	0.03	−0.29	0.17	0.08	−0.5	−0.49	−0.13	0	0	0
Adigudom	0	0	0	−0.26	0	−0.53	−0.25	0.95	−0.06	0	0	0
Dengolat	0	0	0.5	−1.6	0	−0.64	2.08	4.3 *	2.27*	0	0	0
Adishehu	0	0	0	−0.37	−0.07	−0.92	−4.25	−3.0	−0.72	0	0	0
Hiwane	0	0	1.08	−3.22	−0.27	0.56	−4.29	−0.048	1.05	0.11	0	0
Debub	1.2	0	1.9	−2.94	10.04	3	−17.6	−10.55	1.4	−1.65	1.04	0.13

Slope = the change rainfall (mm)/year

*Significant trend at 0.05 significant level

Table 6 Trend of average minimum and maximum temperatures

Temperature	Sen's slope	Mann–K
Average minimum temperature	0.011*	0.245
Average maximum temperature	0.00	0.009
Annual average temperature	0.06	0.068

Mann–K Mann–Kendall test

*Significant trend at 0.05 significant level

Generally, no significant trend in seasonal and annual rainfalls were observed in all meteorological stations of the study area. Except in Hiwane, annual rainfall of all stations has indicated a decreasing trend. Likewise, the previous studies in northern Ethiopia reported that trends of seasonal and annual rainfalls had increasing and decreasing trends, but not statistically significant (Meze-Hausken 2004; Seleshi and Zanke 2004; Viste et al. 2012; Hadgu et al. 2013; Abebe et al. 2022).

Temperature trend analysis

Recorded data for both average minimum and maximum temperature entail a positive trend at both 0.01 and 0.05 significant levels with significant slope for average minimum temperature (Table 6). Many evidences indicated that temperature is increasing throughout the world (Collier et al. 2008; Conway and Schipper 2011; IPCC 2013). The findings of previous research studies in northern Ethiopia and nearby regions are also in agreement with the current result (Gebrehiwot and van der Veen 2013; Addisu et al. 2015; Esayas et al. 2019; Gebrechorkos et al. 2019).

The Sen's slope and Mann–Kendall values of seasonal and monthly maximum and minimum temperature for the station are given in Table 7. The seasonal maximum temperature for all seasons had positive and significant trend at 0.0001, 0.001, and 0.0001 p values, respectively. While trend of minimum temperature was significant only for summer season with 0 p value, and this indicates the summer has been warming which plays a vital role in water balance and water supply.

Out of 12 months, half of them have shown positive significant trend for maximum temperature. About 83% of the months were found in dry and spring seasons. In contrast, positive significant trend in minimum temperature was observed only for July. Generally, MoWIE (2018) revealed that temperature is increasing in all seasons and almost all months, and the rate of evapotranspiration (1600–2100 mm) will continue affecting both surface and groundwater sources of water supply.

Table 7 Seasonal and monthly trend of maximum and minimum temperature for 30 years (1987–2016)

Parameter	Sen's slope											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Maximum temperature	0.038	0.047*	0.05*	0.07*	0.09*	−0.001	0.04	0.05*	0.04	0.04*	0.018	0.021
Minimum temperature	−0.002	0.031	0.035	0.02	0.01	0.022	0.03*	0.02	0.01	−0.01	0.03	0.008

Parameter	Dry		Spring		Summer	
	Sen's slope	Mann–K	Sen's slope	Mann–K	Sen's slope	Mann–K
Maximum temperature	0.046*	0.545	0.065*	0.458	0.047*	0.524
Minimum temperature	0.00049	0.011	0.016	0.122	0.057*	0.485

Mann–K Mann–Kendall test

*Significant trend at 0.05 significant level

Water yield of water supply sources

Figure 9 shows water yield rates of HDWs during construction and in 2017. For most HDWs, water yields were lower in 2017 compared to water yields during construction. Some wells, such as W2, W4, W5, W6, W8, W10, W11, and W19, have higher water yield in 2017 compared to the water yield during construction. Comparing the yield of the wells during the construction time and in 2017, yield has increased by 38%. These HDWs were located in slope less than 5% and in well covered or/and conserved surroundings.

In some wells, measured water yields were similar throughout the depth. This may be either of or due to combination of good potential of groundwater, property of geological formation (Walraevens et al. 2009; Gross 2008), confinement of the geological formation, and position of the entry of recharged water. Most of these wells were covered or/and found near conserved areas.

The common type of improved water source in the study area is groundwater in boreholes equipped with a hand pump and SP. Available studies showed that groundwater recharge and discharge conditions are the reflection of the climatic variables, landscape characteristics, topography (MacDonald et al. 2009; Walraevens et al. 2009; Dragoni and Sukhija 2008; Kahsay et al. 2019), and human impacts, such as agricultural drainage and flow regulation.

The springs which had good water yields were located in grasslands and/or conserved areas. Examples of such SPs were SP1, SP3, SP11, SP14, and SP18 (Fig. 10). SPs, such as SP5, SP6, SP8, SP9, and SP10, showed a decrease in water yield in 2017 by more than 70% compared to yield in the construction time. These SPs were located in slopes between 10 and 35%. Thus, the cause for the reduction in yield could be due to the dramatic decrease of ground water level in sloped areas during dry season (Walraevens et al. 2009).

Impact of climate variability on water yield of water supply sources

Water yield and rainfall

For 86% of the HDWs, annual rainfall was greater in 2016 than before the construction time (Fig. 11). Generally, annual rainfall in 2016 exceeded the long-term average annual rainfall by 17% in Adigudom, by 35% both in Mekelle and Dengolat. In the other stations, the amount of annual rainfall is similar with the long-term annual rainfall. Water yield of HDWs have increased by 38% in 2017 compared to the yield in the construction time. The increased yields were observed for WSSs located nearby to check dams, ponds, and perennial rivers. This change in water yield could be due to enhancement of groundwater recharge from the infiltration of collected water with constructed water harvesting structures (Nedaw and Walraevens 2009; Grum et al. 2016; Kotchoni et al. 2018; Andualem et al. 2020). Regardless of annual rainfall, water yield decreased in 2017 compared to water yield in the construction time for HDWs located in sloped and/or degraded areas. The decrease in water yield in these sloped or degraded areas could be attributed to sudden drain of aquifers and drop of ground water level due to gravity (Walraevens et al. 2009; Calow et al. 2015). Furthermore, Nata and Bheemalingeswara (2010) pointed out that, apart from climatic factor, the yield characteristics of HDWs depend on other factors, such as landform, regolith, fracture characteristics of bedrock, and local groundwater regimes.

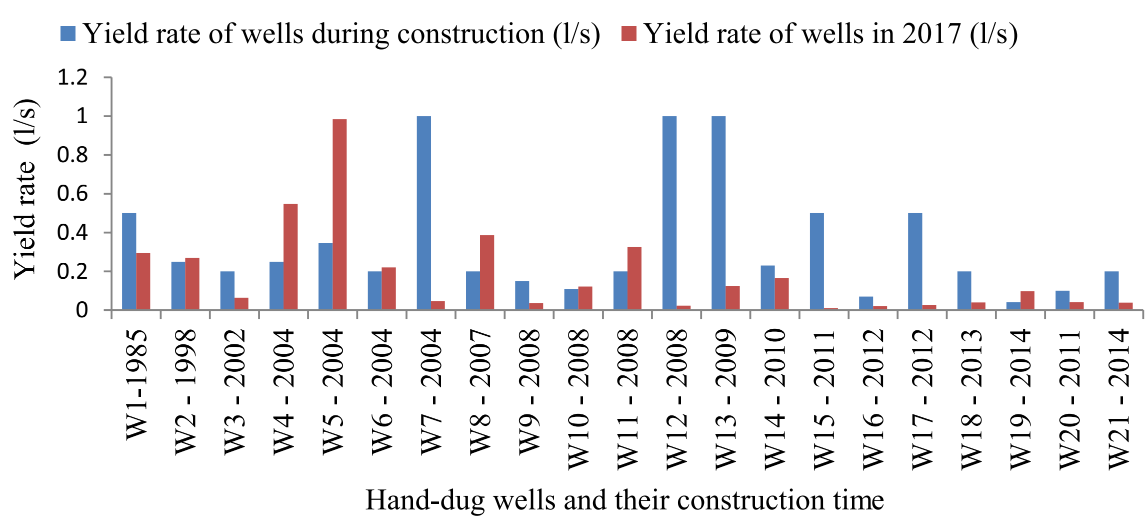

Fig. 9 Comparison of measured yield rate of hand-dug wells during construction and in 2017; W stands for wells tested for yield rate

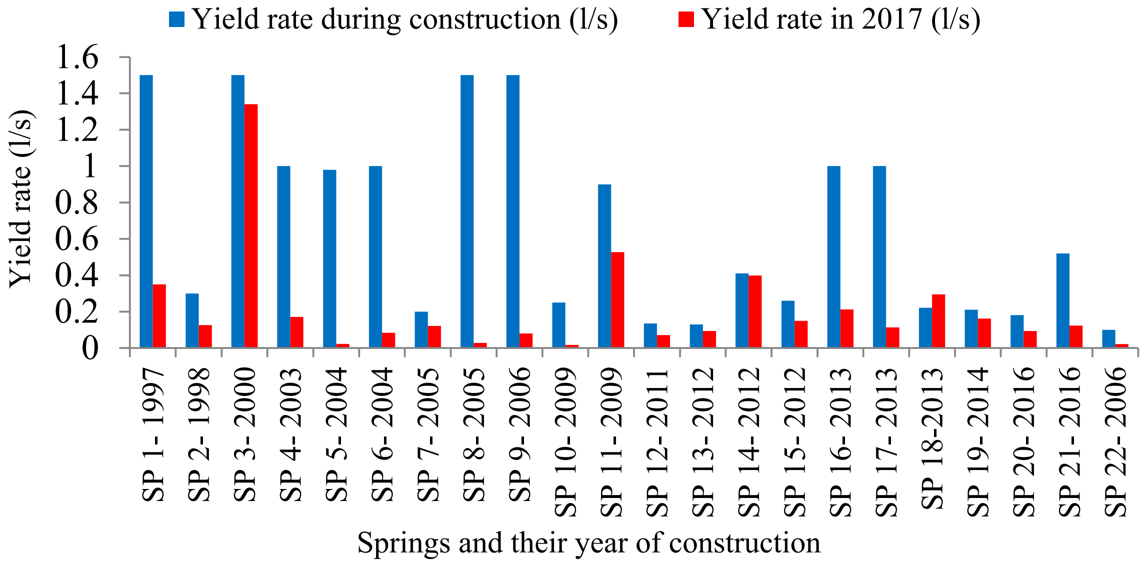

Fig. 10 Comparison of measured water yield rate of springs during construction time and in 2017; SP stands for spring tested for yield rate

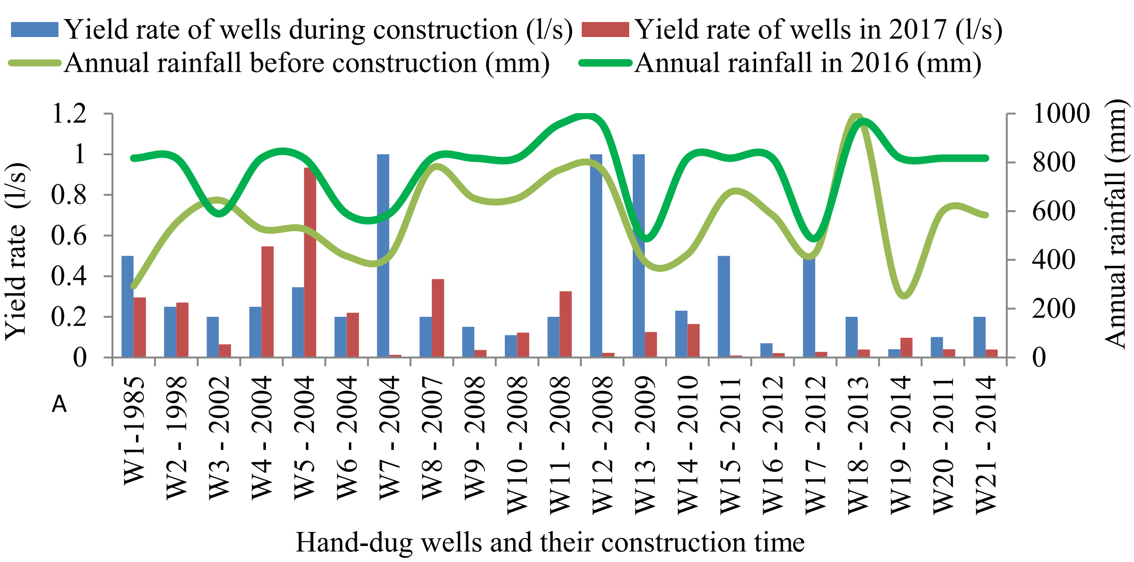

Fig. 11 Rate of water yield of HDWs and rainfall variability. W: wells

For 82% of the SPs, annual rainfall in 2016 is greater than the rainfall during the construction time. The yield of SPs was better in well-managed areas and slopes less than 5%. Only 23% of SPs' yields tested in 2017 have similar yields compared to the yield in the time of construction. For most SPs located in low LULC practices, yields of 2017 were less than during construction period. The decline in yield may be due to decrease in groundwater under poor LULC and overexploitation of water (Walraevens et al. 2009), clogging of SPs' holes over time (Sethi et al. 2020).

Service life of water supply schemes

The results for the service life of rural WSSs in the previous 2 decades were arithmetically decreasing throughout the time (Table 8). Although the number of constructed WSSs have increased over the years (1994–2017), a significant number of these schemes have dried. This result demonstrates that service life of the WSSs was decreasing over the years.

Generally, it can be concluded that in areas having mean annual rainfall of less than 600 mm for two consecutive

Table 8 Summary of service life of water supply schemes (WSSs)

Time of drying	1994–1998	1999–2003	2004–2008	2009–2013	2014–2017
Number of dried WSS	12	5	15	24	23
Average age in years	14.9	7	5.9	3.5	0.8

years, water supply sources were susceptible to decrease their yield and/or dry up. The impact of rainfall amount on dryness of water supply source was higher in steep and rugged topography. If a well became dry, either the annual rainfall amount of two consecutive years was low and/or its land use/land cover has changed. In areas such as the northern Ethiopia, in which the total annual rainfall is concentrated mainly in the months of June–September, the susceptibility of the rural WSSs to dryness is high and likely to cause a decrease in water yield of the schemes.

Water supply and demand fluctuation

The water demands of the study area were determined by gathering data for the number of users in each WSS and a water consumption of rate of 25 L/capita/day, a planned and expected water supply service level standard for rural areas during the Ethiopian growth and transformation plan 2 or GTP-2 (MoWIE 2015).

About 19% of wells and SPs fully satisfy the rural water demand requirements for GTP-2. However, 68% of water yield tests conducted for wells and SPs showed far below the requirement of the proposed water demand per capita for household. This shows that there is still a large gap between water demand and supply in rural areas of the study area. The disparity in water demand and supply has the impact during the dry season when demand for water is the highest. The deficiency of water supply of wells and SPs analyzed for the study period is summarized in Fig. 12. The *x*-axis shows scheme type, codes, and their corresponding construction period. The positive values indicate WSSs with excess water, whereas the negative values indicate a deficiency in water supply compared to demand.

Relation between rainfall and water yield

Correlation analysis of annual rainfall and water yield using Pearson correlation coefficient showed variable relationships (Table 9). For HDWs, the correlation between rainfall and water yield was positive ($r = 0.25$) and non-significant ($p > 0.05$). The correlation between water yield of HDWs and rainfall, however, improved ($r = 0.48$) for wells located in slope gradients less than 5% but still non-significant ($p > 0.05$). This is complemented by the negative ($r = -0.44$) and significant ($p < 0.05$) correlation between water yield and slope gradient.

For SPs, the relationship between water yield and annual rainfall was moderate ($r = 0.54$) and significant ($p < 0.05$), showing the dependency of water yield of SPs on amount of rain. The correlation between water yield and slope

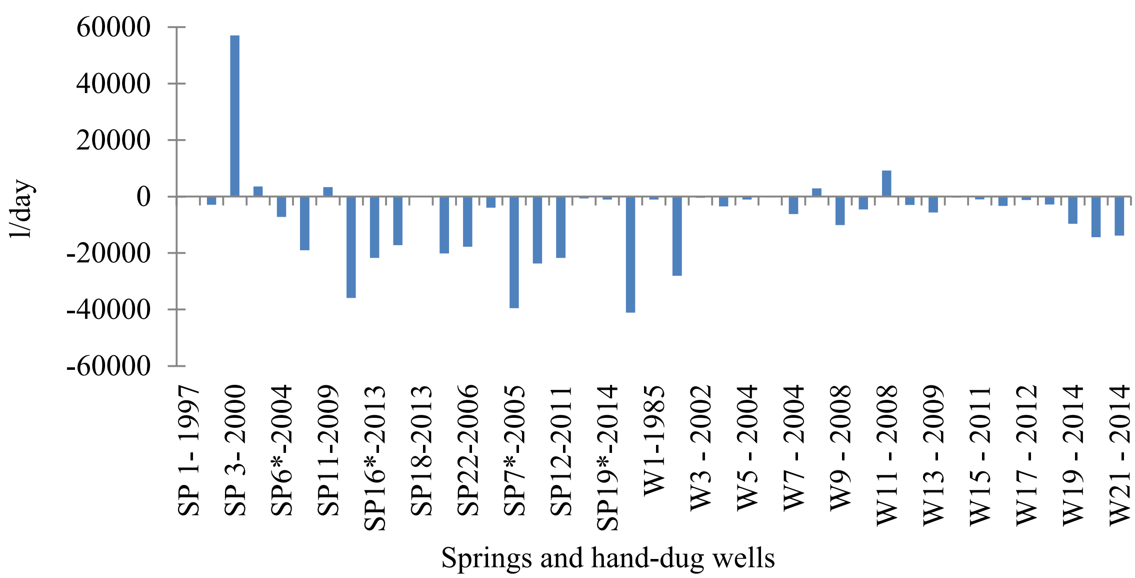

Fig. 12 Status of rural water supply schemes (hand-dug wells and springs) in terms of demand and supply differences. SP*: springs with gates; W: wells

Table 9 Correlation results with all the parameters

Parameters	Wells' Yield	Springs' yield	Annual rainfall	Slope gradient	Slope gradient < 5%	
					Annual rainfall	Slope gradient
Pearson correlation (r) result with wells' yield	1	–	0.25	−0.44*	0.48	−0.48
2-tailed *p* value	–	–	0.51	0.048	0.119	0.113
Pearson correlation (r) result with springs' yield	–	1	0.54*	−0.31	–	–
2-tailed *p* value	–	–	0.043	0.25	–	–

gradient for SPs was, however, negative ($r = -0.3187$) and non-significant ($p > 0.05$). Generally, water yield of SP7 is more dependable on rainfall than slope gradient. Other studies also indicated that WSSs become more susceptible to a decrease in water yield in steep slope gradients. In these areas, the possibility of the wells being dry is high due to will natural draining of water within an aquifer to the lower parts of a catchment (Calow et al. 2015).

Conclusions

This study has presented a detailed analysis on the impact of temporal and spatial climate variability on sustainability of rural water supply schemes in the Enderta and Hintalo-Wejerat woreda, northern Ethiopia. Based on the findings of this study, the following conclusions were drawn.

Trend analysis on rainfall indicated that no significant change was perceived in annual and seasonal rainfall, except summer season for Dengolat station. However, rainfall analysis using coefficient of variation, precipitation concentration index and standardized rainfall anomaly indicated a very high rainfall variability in the meteorological stations. Moreover, about 70% annual rainfall of the stations was mainly concentrated on 2 months, namely July and August. On the other hand, an overall increasing trend in average annual minimum and maximum temperatures was observed for the study area. The average annual maximum temperature of the study area has been increasing by about 0.34 °C per decade. Moreover, average annual minimum temperature has been increasing by about 0.68 °C per decade. This shows that the northern Ethiopian part is warming faster than the national average warming which is 0.25 °C per decade.

Results of most hand-dug wells and springs showed that water yield has been decreasing for most schemes except some hand-dug wells which were located in well-managed land uses. The combined effect of climate variability and concentration of rainfall in few months of the year is impacting sustainable use of rural WSS in northern Ethiopia. Most water supply schemes located in mountainous areas are subjected to drying, while others located nearby to check dams, reservoirs, ponds, and perennial rivers were resilient to climate variability.

Acknowledgements The authors would like to thank the Ethiopian Meteorological Agency for providing daily rainfall and temperature data for the study area and Norwegian Agency for Development Cooperation (NORAD) (MU-NMBU institutional collaboration with grant number: CRPO/EiT-M/MU-HU-NMBU/MSc/007/09) for financial support. The authors extend their appreciation to the generosity and hospitality of the peoples of Enderta and Hintalo Wejerat for their unconditional support during the field work.

Author contributions Muruts Getachew contributed to the conceptualization, data collection, data analysis, and preparing of the original draft manuscript. Bizuneh Asfaw Abebe contributed to formulating the objectives, methods, project administration, supervision, review, and editing. Berhane Grum contributed to the conceptualization, formulating of the overall project, supervision, and structuring of the manuscript.

Funding This research was funded by Mekelle University-Norwegian University of Life Sciences (MU-NMBU) (Project Registration Number: Ref. No: CRPO/EiT-M/MU-HU-NMBU/MSc/007/09).

Data availability The recorded daily rainfall and temperature data of the currently existing meteorological stations were obtained from Ethiopian National Meteorological Agency. Water supply schemes data and construction history were obtained from Tigray Bureau of Water Resources.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abebe BA, Grum B, Degu AM, Goitom H (2022) Spatio-temporal rainfall variability and trend analysis in the Tekeze-Atbara River basin, northwestern Ethiopia. Meteorol Appl 29(2):e2059. https://doi.org/10.1002/met.2059

Abrha MG, Simhadri S (2015) Local climate trends and farmers' perceptions in southern Tigray, northern Ethiopia. Int J Environ Sustain 4(3):11–28. https://doi.org/10.3844/ajessp.2015.262.277

Addisu S, Selassie YG, Fissha G, Gedif B (2015) Time series trend analysis of temperature and rainfall in Lake Tana subbasin, Ethiopia. Environ Syst Res 4(25):1–12. https://doi.org/10.1186/s40068-015-0051-0

Central Statistical Agency (CSA) of Ethiopia (2013) Population projection of Ethiopia for all regions at woreda level from 2014–2017. Addis Ababa, Ethiopia

National Meteorological Agency (NMA) of Ethiopia (2001) Report submitted to initial national communication of Ethiopia to the United Nations Framework Convention on Climate Change (UNFCCC). Addis Ababa, Ethiopia

Alem F, Abebe BA, Degu AM, Goitom H, Grum B (2022) Assessment of water harvesting potential sites using GIS-based MCA and a hydrological model: case of Werie catchment, northern Ethiopia. Sustain Water Resour Manage 70(8):1–19. https://doi.org/10.1007/s40899-022-00652-x

Amah EA, Anam GS (2016) Determination of aquifer hydraulic parameters from pumping test data analysis: a case study of Akpabuyo coastal plain sand aquifers, cross river state, S-E Nigeria. IOSR J Appl Geol Geophys 4:1–8. https://doi.org/10.9790/0990-04110108

Andualem TG, Hagos YG, Teka AH (2020) Rainwater harvesting potential assessment for non-potable use in urban areas. Sustain Water Resour Manage 104(6):1–8. https://doi.org/10.1007/s40899-020-00464-x

Awulachew SB, Yilma AD, Loulseged M, Loiskandl W, Ayana M, Alamirew T (2007) Water resources and irrigation development in Ethiopia. Colombo, Sri Lanka: International Water Management Institute (IWMI Working Paper 123)

Balasubramanian A (2017) Procedure for conducting pumping tests. University of Mysore, p. 1–10. https://doi.org/10.13140/RG.2.2.18948.32641

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP, Eds. (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva

Bewket W, Conway D (2007) A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int J Climatol 27:1467–1477. https://doi.org/10.1002/joc.1481

Bonsor HC, MacDonald AM, Calow RC (2011) Potential impact of climate change on improved and unimproved water supplies in Africa. In: Hester RE, Harrison RM (eds) Sustainable Water, Issues in Environmental Science and Technology. Royal Society of Chemestery, London, pp 25–45

Buishand T (1982) Some methods for testing the homogeneity of rainfall records. J Hydrol 58:11–27. https://doi.org/10.1016/0022-1694(82)90066-X

Calow R, Ludi E, McKenzie A, Seifu K (2015) Climate and environmental risk screening for rural water supply in Ethiopia. Overseas Development Institute (ODI), London

Central Statistical Agency (CSA) of Ethiopia (2017) Water quality in Ethiopia. Results from 2016 Ethiopia socioeconomic Survey (ESS), Report by the Central Statistical Agency of Ethiopia in collaboration with the Ministry of Water, Irrigation and Electricity (MoWIE), LSMS, World Bank, UNICEF, WHO. Volume 7(2)

Collier P, Conway G, Venables T (2008) Climate change and Africa. Oxford Rev Econ Policy 24(2):337–353. https://doi.org/10.1093/oxrep/grn019

Conway D, Schipper ELF (2011) Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. Global Environ Change 21:227–237. https://doi.org/10.1016/j.gloenvcha.2010.07.013

De Luís M, González-Hidalgo JC, Raventos J, Sanchez JR, Cortina J (1999) Spatial analysis of rainfall trends in the region of Valencia (East Spain). Int J Climatol 20:1451–1469. https://doi.org/10.1002/1097-0088(200010)

Dragoni W, Sukhija BS (2008) Climate change and groundwater: a short review. Geol Soc Lond 288:1–12. https://doi.org/10.1144/SP288.1

Esayas B, Simane B, Teferi E, Ongoma V, Tefera N (2019) Climate variability and farmers' perception in southern Ethiopia. Adv Meteorol 2019:7341465. https://doi.org/10.1155/2019/7341465

FAO (Food an Agriculture Organization) (1984) Geo-morphology and soils. Assistance to land use planning project, Ethiopia. Field document 2, AG: DP/ETH/781003, Addis Ababa, Ethiopia

Gao P, Li P, Zhao B, Xu R, Zhao G, Sun W, Mu X (2017) Use of double mass curves in hydrologic benefit evaluations. Hydrol Process 31:4639–4646. https://doi.org/10.1002/hyp.11377

Gebrechorkos SH, Hülsmann S, Bernhofer C (2019) Long-term trends in rainfall and temperature using high-resolution climate datasets in east Africa. Sci Rep 9:11376. https://doi.org/10.1038/s41598-019-47933-8

Gebrehiwot T, van der Veen A (2013) Assessing the evidence of climate variability in the northern part of Ethiopia. J Dev Agric Econ 5(3):104–119. https://doi.org/10.5897/JDAE12.056

Gross E (2008) A manual pumping test method for characterizing the productivity of drilled wells equipped with rope pumps. MSc Thesis, Michigan Technological University, USA

Grum B, Hessel R, Kessler A, Woldearegay K, Yazew E, Ritsema CJ, Geissen V (2016) A decision support approach for the selection and implementation of water harvesting techniques in arid and semi-arid regions. Agric Water Manage 173:35–47. https://doi.org/10.1016/j.agwat.2016.04.018

Hadgu G, Tesfaye K, Mamo G, Kassa B (2013) Trend and variability of rainfall in Tigray, northern Ethiopia: analysis of meteorological data and farmers' perception. Acad J Agric Res 1(6):88–100. https://doi.org/10.15413/ajes.2013.0117

Ibrahim KO, Gomo M, Oke SA, Matamanda AR (2021) Hand-dug wells in rural areas of developing countries. Sustain Water Resour Manage 7:42. https://doi.org/10.1007/s40899-021-00523-x

IPCC (International Panel on Climate Change) (2013) The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Kahsay KD, Pingale SM, Hatiye SD (2017) Impact of climate change on groundwater recharge and base flow in the sub-catchment of Tekeze basin, Ethiopia. Groundw Sustain Dev 6:121–133. https://doi.org/10.1016/j.gsd.2017.12.002

Kahsay GH, Gebreyohannes T, Gebremedhin MA, Gebrekirstos A, Birhane E, Gebrewahid H, Welegebriel L (2019) Spatial groundwater recharge estimation in Raya basin, northern Ethiopia: an approach using GIS based water balance model. Sustain Water Resour Manage 5:961–975. https://doi.org/10.1007/s40899-018-0272-2

Kiyan A, Gheibi M, Moezzi R, Behzadian K (2023) Smart dashboard of water distribution network operation: a case study of Tehran. Environ Ind Lett. https://doi.org/10.15157/EIL.2023.1.1.46-63

Kotchoni DOV, Vouillamoz JM, Lawson FMA, Adjomayi P, Boukari M, Taylor RG (2018) Relationships between rainfall and groundwater recharge in seasonally humid Benin: a comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers. Hydrogeol J 27:447–457. https://doi.org/10.1007/s10040-018-1806-2

Kumar V, Jain SK, Singh Y (2010) Analysis of long-term rainfall trends in India. Hydrol Sci J 55(4):484–496. https://doi.org/10.1080/02626667.2010.481373

Landau S, Everitt BS (2004) A handbook of statistical analyses using SPSS. CRC Press LLC, New York

MacAllister DJ, MacDonald AM, Kebede S, Godfrey S, Calow R (2020) Comparative performance of rural water supplies during drought. Nat Commun 10:1099. https://doi.org/10.1038/s41467-020-14839-3

MacDonald AM, Calow RC, Macdonald DM, Darling WG, Dochartaigh BE (2009) What impact will climate change have on rural groundwater supplies in Africa. Hydrol Sci J 64:690–703. https://doi.org/10.1623/hysj.54.4.690

MacDonald AM, Bonsor HC, Béó D, Taylor RG (2012) Quantitative maps of groundwater resources in Africa. Environ Res Lett 7:024009. https://doi.org/10.1088/1748-9326/7/2/024009

Mavromatis T, Stathis D (2011) Response of the water balance in Greece to temperature and precipitation trends. Theor Appl Climatol 104:13–24. https://doi.org/10.1007/s00704-010-0320-9

Meze-Hausken E (2004) Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. Climate Res 27:19–31

Ministry of Water, Irrigation and Electricity (MoWIE) (2016) Climate resilient water safety plan for rural water supply training manual. Federal Democratic Republic of Ethiopia, Ministry of Water, Irrigation and Electricity, Addis Ababa

Ministry of Water, Irrigation and Electricity (MoWIE) (2015) Second growth and transformation national plan for the water supply and sanitation sub-sector (2015/16 – 2019/20). Federal Democratic Republic of Ethiopia, Ministry of Water, Irrigation and Electricity, Addis Ababa

Ministry of Water, Irrigation and Electricity (MoWIE) (2018) Development of sustainable water supply, sanitation and hygiene program in drought prone areas of Ethiopia. Sub-programme document. Federal Democratic Republic of Ethiopia, Ministry of Water, Irrigation and Electricity, Addis Ababa

Nata T, Bheemalingeswara K (2010) Prospects and constraints of household irrigation practices, Hayelom watershed, Tigray, northern Ethiopia. Momona Ethiop J Sci 2(2):87–109. https://doi.org/10.4314/mejs.v2i2.57676

Nedaw D, Walraevens K (2009) The positive effect of micro-dams for groundwater enhancement: a case study around Tsinkanet and Rubafeleg area, Tigray, northern Ethiopia. Momona Ethiop J Sci 1(1):59–73. https://doi.org/10.4314/mejs.v1i1.46041

Ngongondo C, Yu-Xu C, Gottschalk L, Alemaw B (2011) Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. Theor Appl Climatol 106(1–2):79–93. https://doi.org/10.1007/s00704-011-0413-0

Nyahunda L, Tirivangasi HM (2019) 'Challenges faced by rural people in mitigating the effects of climate change in the Mazungunye communal lands, Zimbabwe', Jàmbá. J Disaster Risk Stud 11(1):a596. https://doi.org/10.4102/jamba.v11i1.596

Oliver J (1980) Monthly precipitation distribution: a comparative index. Prof Geog 32:300–309. https://doi.org/10.1111/j.0033-0124.1980.00300.x

Rosell S (2011) Regional perspective on rainfall change and variability in the central highlands of Ethiopia, 1978–2007. Appl Geogr 31:329–338. https://doi.org/10.1016/j.apgeog.2010.07.005

Salmi T, Määttä A, Anttila P, Ruoho-Airola T, Amnell T (2002) Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates-the excel template application MAKESENS. Finnish Meteorological Institute, Publications on Air Quality No. 31, Helsinki

Seleshi Y, Zanke U (2004) Recent change in rainfall and rainy days in Ethiopia. Int J Climatol 24(8):973–983. https://doi.org/10.1002/joc.1052

Sethi RR, Ambast SK, Panda B, Das M (2020) Quantification of recharge from the rainwater harvesting structures - a case study in hard rock area of Odisha (India). Sustain Water Resour Manage 6:84. https://doi.org/10.1007/s40899-020-00443-2

Tabari H, Marofi S, Aeini A, Talaee P, Mohammadi K (2011) Trend analysis of reference evapotranspiration in the western half of Iran. Agric Forest Meteorol 151:128–136. https://doi.org/10.1016/j.agrformet.2010.09.009

Talema A (2023) Causes, negative effects, and preventive methods of water pollution in Ethiopia. Qual Assur Saf Food 15(2):129–139

Taylor R, Todd M, Kongola L, Maurice L, Nahozya E, Sanga H (2013) Evidence of the dependence of groundwater resources on extreme rainfall in east Africa. Nat Clim Change 3:374–378. https://doi.org/10.1038/nclimate1731

Tigray Bureau of Water Resources (TBoWR) (2019) Annual report for water supply coverage, Mekelle, Tigray

Twisa S, Buchroithner MF (2019) Seasonal and annual rainfall variability and their impact on rural water supply services in the Wami River basin, Tanzania. Water 11:2055. https://doi.org/10.3390/w11102055

Viste E, Korecha D, Sorteberg A (2012) Recent drought and precipitation tendencies in Ethiopia. Theor Appl Climatol 112(3–4):535–551. https://doi.org/10.1007/s00704-012-0746-3

Walraevens K, Vandecasteele I, Martens K, Nyssen J, Moeyersons J, Gebreyohannes T, De Smedt F, Poesen J, Deckers J, Van Camp M (2009) Groundwater recharge and flow in a small mountain catchment in northern Ethiopia. Hydrol Sci J 54(4):739–753. https://doi.org/10.1623/hysj.54.4.739

Wang J, Hou B, Jiang D, Xiao W, Wu Y, Zhao Y, Zhou Y, Guo C, Wang G (2016) Optimal allocation of water resources based on water supply security. Water 8:237. https://doi.org/10.3390/w8060237

Wangdi N, Om K, Thinley C, Drukpa D, Dorji T, Darabant A, Chhetri PD, Ahmed IU, Staudhammer CL, Jandl R, Schindlbacher A, Hietz P, Katzensteiner K, Godbold D, Gratzer G (2017) Climate change in remote mountain regions: A throughfall-exclusion experiment to simulate monsoon failure in the Himalayas. Mt Res Dev 37(3):294–309. https://doi.org/10.1659/mrd-Journal-D-16-00097.1

WHO and UNICEF (2023) Progress on household drinking water, sanitation and hygiene 2000–2022: Special focus on gender. WHO/UNICEF, New York

WHO (2009) The resilience of water supply and sanitation in the face of climate change. Summary and Policy Implications Vision 2030

WHO, UNICEF, World Bank (2022) State of the world's drinking water: an urgent call to action to accelerate progress on ensuring safe drinking water for all. Geneva: WHO; Licence: CC BY-NC-SA 3.0 IGO

WHO/UNICEF Joint Monitoring Programme (JMP) (2015) Progress on sanitation and drinking water, update and MDG assessment

World Bank (2017) Ethiopia Water Supply, Sanitation and Hygiene Project. 2022 Global Report

Yue S, Wang C (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour Manage 18:201–218. https://doi.org/10.1023/B:WARM.0000043140.61082.60