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Water Quality Status of *Washa* and *Borale* Reservoirs Using Physicochemical Parameters and Macroinvertebrates in Ethiopian Central Highlands

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ABSTRACT

Washa and *Borale* reservoirs are important in regulating climatic and ecological conditions and providing various economic services. However, water quality and/or ecological health status of reservoirs has not yet been properly assessed in Ethiopia. Therefore, the main purpose of this study was to assess the water quality status of the *Washa* and *Borale* reservoirs/ wetlands located in North Shewa Zone of Ethiopian Central Highlands. Their water quality status was assessed using water physicochemical parameters and macroinvertebrates in December 2020 and November 2021. The results recorded from *Washa* Reservoir showed that the concentration of nitrate, phosphate, ammonia and silica on average was 69 µg/L, 53.52 µg/L, 188.86 µg/L and 14 µg/L, respectively. Similarly, the concentration of nitrate, phosphate, ammonia and silica obtained from *Borale* Reservoir on average was 43.5 µg/L, 32.6 µg/L, 50.0 µg/L and 109.8 µg/L, respectively. The concentration of ammonia was found to be high in both reservoirs indicating the presence of organic contamination. The total number of macroinvertebrates collected from *Washa* and *Borale* reservoirs were 519 and 789, respectively. Eight families belonging to three orders were recorded in *Washa* Reservoir whereas seven families belonging to four orders were recorded in *Borale* Reservoir. Order Hemiptera was represented by 5 families, Coleptera by two and Ephemeroptera by one in *Washa* Reservoir. Similarly, Hemiptera was represented by four families compared to other orders in *Borale* Reservoir. High dominance of tolerant macroinvertebrate families and absence of sensitive families indicated ecological instability and pollution in *Borale* Reservoir. Besides, ecological disturbance and pollution are observed in Washa Reservoir. Hence, human interference and cattle drinking should be regulated before both reservoirs are impaired permanently.

Keywords: Central Ethiopia, Evaluation, Wetlands, Water parameters, Water pollution

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1. INTRODUCTION

1.1. Background and Justification

Reservoirs are lacustrine wetlands with immense ecological and economic importance. They can help in checking floods, generating electricity, providing storage for drinking water and irrigation etc. Such systems are particularly critical for supporting human livelihoods in Africa (Chapman *et al*., 2001; Rebelo *et al*., 2010). They also play vital roles in retaining runoff and sediments, and in purifying wastewaters so that they serve as sink, runoff receivers, wastewater filters and transformation systems of pollutants. Moreover, they provide many important functions including habitat and food provision for plants and animals, and processing of pollutants derived from extensive agriculture and urban development (Wetzel, 2006). Especially, wetlands are habitats (living areas) to remarkable number of animals, plants, macroinvertebrates and amphibians (U.S. EPA, 2002b). Most of the aquatic flora and fauna depend entirely on wetlands and are attracted by the presence of high habitat qualities (Zedler and Kercher, 2005).

Despite providing such biodiversity conservation and socio-economic services, such lacustrine wetlands have severely been degraded worldwide, particularly in developing nations like Ethiopia. The greatest threats and causes of the wetland degradation and loss are mainly associated with anthropogenic activities. The main anthropogenic activities are cultivation, drainage, plantation, overgrazing, and water extraction and waste discharges (Crecious and Lazarou, 2013; Moges *et al*., 2018). Moreover, development activities such as soil excavation, unplanned construction and urbanization, and excessive exploitation of resources of wetlands (Schuyt, 2005) are the other major pressures to degradation and loss of such reservoirs. Generally, these activities have severely affected the wetland ecosystems by altering their flora composition, physicochemical characteristics of waters, and their physical structures. Furthermore, dumping domestic and industrial wastes predominantly in the urban wetlands (Beyene *et al*., 2009) and adding nutrients via runoff mainly to agricultural wetlands are other sources of pollution and ecological degradation. As a consequence, many wetlands in Ethiopia are under severe threats (Ambelu *et al*., 2013; Moges *et al*., 2018).

Nearly 690 households are living in the present study area (01 kebele) of *Debre Birhan Town.* Of which 58 and 149 households, belonging to *Washa* and *Borale*, respectively, have irrigable lands at downstream and harvest various vegetables and cereal crops at least twice a year by drawing water directly from the reservoirs. Moreover, these reservoirs provide water for domestic uses and animal drinking and recreational services to the surrounding communities. The reservoirs also support different kinds of birds besides aquatic vegetation. Moreover, farming and grazing activities are practiced in the catchments of these reservoirs. As a result, these two reservoirs are under threats like that of other surface water bodies found in Ethiopia owing to water extraction for irrigation at downstream and livestock drinking, faming, and grazing practices. Thus, this situation calls for immediate assessment of water quality of the two reservoirs. For evaluating the water quality/pollution extent of the two reservoirs, physicochemical parameters and macroinvertebrates are used because the integrated use of physicochemical characteristics and biological communities in surface water of wetlands/ reservoirs helps to determine their condition or health (U.S. EPA, 2002a) in a better way. Sharma and Rawat (2009) also reported that macroinvertebrates and water quality are interrelated as they are indicators of water quality and they easily respond to pollutants and eutrophication. Thus, the major physicochemical parameters and macroinvertebrate communities are analyzed for evaluating the water quality of the present reservoirs. Therefore, the specific objectives of this study are to: (1) analyze the major water quality parameters, (2) calculate the macroinvertebrates composition, abundance and diversity using various Shannon-Weiner diversity indices, and (3) determine the water quality status of the two reservoirs based on the results of both water quality parameters and various indices for macroinvertebrate communities.

2. MATERIALS AND METHODS

2.1. Description of the study area

This study was carried out in *Washa* and *Borale* Reservoirs/ wetlands located at the periphery of Debre Berhan town, but now included to be the part of 01 Kebele (which is the smallest governmental administrative unit in Ethiopia) of DBU of North Shewa Zone, Ethiopian Central Highlands (Figure 1). The *Washa* and *Borale* sites are 10 and 15 km far from the center of the town, with altitudes of 2763 and 2832 meters above sea level, respectively. The *Washa* site is positioned at $9^0$39'45" latitude and $39^0$32'45" longitude; whereas the *Borale* site is located at $9^0$39'62" latitude and $39^0$32'36" longitude. The temperature of DBT ranges from the mean annual minimum temperature of 2.3^0c to the mean annual maximum temperature of 22^0c. The mean annual rainfall of the study area is 906 mm.

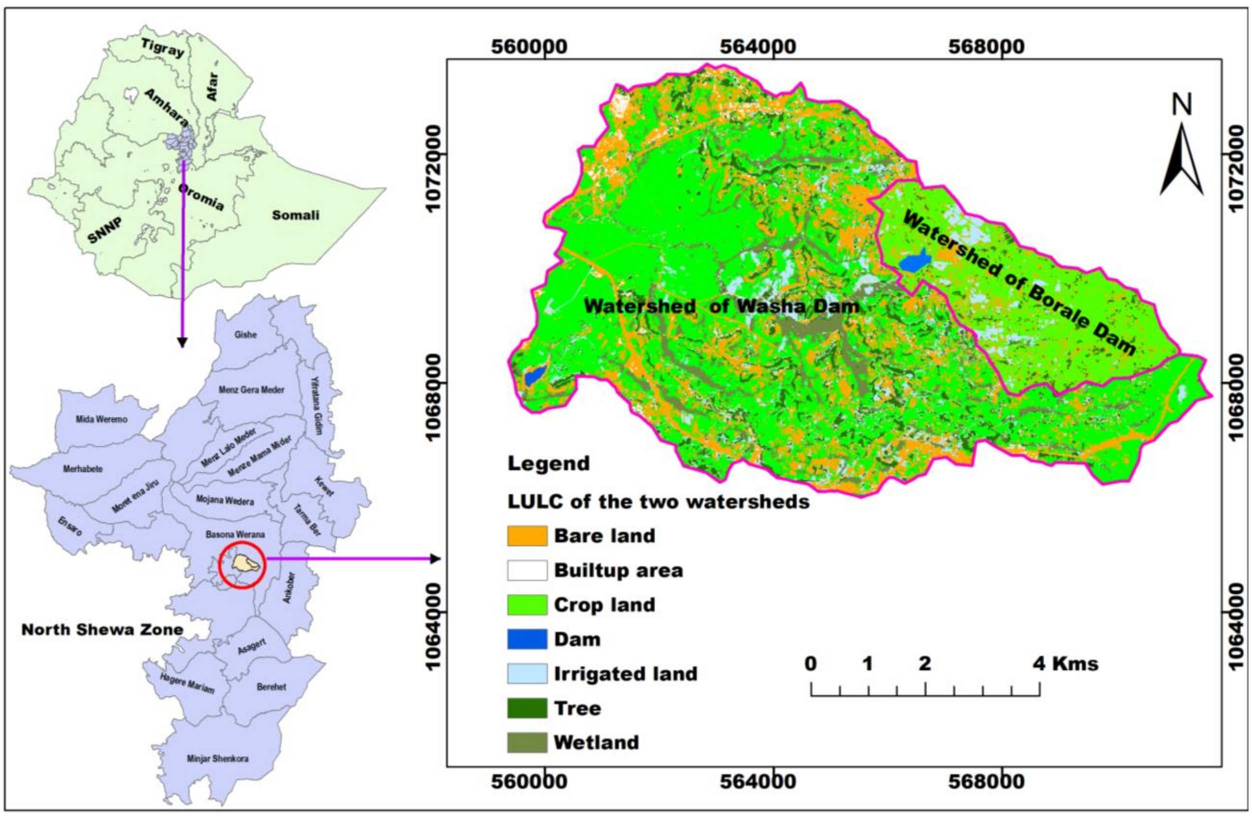

Figure 1: A map of the study area (Source: Moges and Mebrate 2022)

2.2. Study design and sampling

Preliminary survey was conducted on both reservoirs in November, 2020 to gather general information on the physical characteristics of the study area such as watershed features, littoral vegetation, and human pressures. Accordingly, the sites for habitat quality assessment were selected purposively in both reservoirs based on the stressor types (distance from human settlements and anthropogenic effects) and accessibility for quantitative study. For habitat quality assessment, three habitat plots: hab-plot “A’’, hab-plot “ B’’ and hab-plot “C’’ were selected following Lake Habitat Survey (LHS) procedure as outlined in McGoff and Irvine (2009). Each hab-plot covered approximately 100 m of shoreline length. The assessment was done visually and scored through observation.

2.3. Sampling sites of the two wetlands

2.3.1. Sampling sites of *Washa*

Hab-Plot ‘‘A’’: This plot is located in the Northwest of *Washa* Wetland. The site is characterized by sparsely distributed emergent macrophytes and highly exposed to animal interactions.

Hab-Plot ‘‘B’’: This site is bordered by agriculture land. The topography of the site is slant.

Hab-Plot ‘‘C’’: This site is characterized by stony bedrock or sediment and relatively sheltered by the dam.

2.3.2. Sampling sites of *Borale* Wetland

Hab-Plot ‘‘A’’: This plot has no buffer and characterized by cattle watering, agriculture practices, high rate of siltation.

Hab-Plot ‘‘B’’: No agricultural activity is observed in this site. Relatively, it is vegetated and has a buffer. More cattle watering is observed.

Hab-Plot ‘‘C’’: This site is characterized by stony bedrock or sediment and relatively protected.

2.4. Sampling procedures and laboratory analysis of water and macroinvertebrate samples

Sampling was done in December 2020 and November 2021. Each wetland was sampled two times: first in a dry season and second in a wet season. Dissolved oxygen, electrical conductivity, water temperature, and pH were measured *in situ* using pre-calibrated multimeter hand-held probe, model HQ40D. Replicated composite water samples were collected with a 1L plastic bottle from each site, labeled with collection point, stored in an ice box prior to analysis and transported to Addis Ababa Limnology Laboratory. In the laboratory, water samples were filtered through 0.45 µm glass fiber filters (GF/F). Then Nitrate (μgL^{-1}) was measured using cadmium reduction and phosphate (μgL^{-1}) was measured using ascorbic acid methods according to spectrophotometer (HACH, DR/2010, USA) procedures as outlined in APHA (1999). Then concentrations of nutrients were calculated. Ammonia was analyzed by the Phenate Method whereas Dissolved SiO_2 (only Molybdate reactive Silica) was analyzed using Molybdosilicate method following APHA et al. (1999) guideline.

Benthic macroinvertebrates were sampled using D-frame net with mesh size of 500µm (Baldwin *et al*., 2005). The net was moved in a vigorous action for 5 minutes at each site to dislodge macroinvertebrates attached to substrates (Baldwin *et al*., 2005). Macroinvertebrates were sorted out from other debris and then were preserved using 4% formalin, placed into polyethylene plastic bags, labeled and transported to Zoological Sciences Laboratory of Debre Berhan University (DBU) for identification and enumeration. Macroinvertebrates in the samples were identified by family level using combination of keys (Gerber and Gabriel, 2002; Bouchard, 2012) and a dissecting microscope. Subsequently enumeration was done following Baldwin *et al*. (2005).

2.5. Data analysis

The presence of significant variations between the sites in terms of measured physico-chemical parameters and abundance of macroinvertebrates was tested using one-way ANOVA followed by TUKEY test for significant variations.

3. RESULTS

3.1. Physico-chemical parameters of the reservoirs

Concentration of nitrate, phosphate, ammonia, and silica ranged between 44.86- 89 µg/L, 38.8- 72.7 µg/L, 131.57- 280 µg/L and 11.02- 22 µg/L (Table 1) in *Washa* Reservoir, consecutively. whereas, At *Borale* Reservior, however, the concentration was different: 3.4- 89.14 µg/L, 0.8- 52.8 µg/L, 20- 93 µg/L and 17.7- 131 µg/L (Table 2). All measured physico-chemical variables in both reservoirs showed significant variations seasonally. High concentration was noticed during post-rainy season (Table 3 and 4). However, phosphate (SRP) and nitrate ($P<0.05$) showed significant spatial variation in *Washa* Reservoir; whereas, these variations were brought due to Nitrate, Silica, and DO ($P<0.05$) in *Borale* Reservoir. Spatial comparison between sites indicated higher concentration of soluble reactive phosphate (SRP), DO, and ammonia in Hab-Plot A at *Washa* Reservoir, while nitrate was higher in Hab-Plot B (Table 3). Dissolved Oxygen level was the lowest in Hab-Plot B (Table 3). In *Boral*e Reservior, Hab-Plot C showed significantly higher nitrate ($P<0.05$) and lower Silica ($P<0.05$) than the other two sites (Table 4). Dissolved oxygen was significantly highest at Hab-Plot A compared to the other two sites (Table 4). The other parameters didn't show significant variations among sites in both reservoirs. Conductivity and pH were relatively higher in *Borale* Reservoir. However, temperature and dissolved oxygen level were comparable in these two reservoirs (Table 3 and 4).

Table 1: Physicochemical parameters of *Washa* Wetland

Parameters	Min	Max	Average	Standard deviation
Nitrate (µg/L)	44.86	89	69	14.8
Phosphate(µg/L)	38.8	72.7	53.52	10.36
Ammonia(µg/L)	131.57	280	188.86	46.8
Silica(µg/L)	11.02	22	14.9	3.99
pH	6.2	8	7	0.9
Temperature (^{o}C)	16.3	20	18.4	1.9
DO (mg/L)	6.5	10	7.9	1.8
Conductivity (µS/cm)	18.64	21.12	19.9	1.2

Table 2: Physico-chemical parameters of *Borale* Wetland

Parameters	Min	Max	Average	Standard deviation
Nitrate (µg/L)	3.43	89.14	43.5	32.65
Phosphate (µg/L)	0.8	52.8	32.6	16.78
Ammonia (µg/L)	20.14	93	50	24.22
Silica (µg/L)	17.7	139.1	109.8	39.85
pH	6.27	8.5	7.9	0.8
Temperature (^{o}C)	10.5	21	16.4	3.7
DO (mg/L)	3.8	8.5	6.7	1.8
Conductivity (µS/cm)	55	86.4	73.2	10.2

Table 3: Physicochemical parameters during dry and wet season taken in *Washa* Wetland

	Parameters	Dry Season			Wet Season		
		Plot A	Plot B	Plot C	Plot A	Plot B	Plot C
1	SRP (µg/L)	58.4	45.1	41.8	70.5	55.6	49.35
2	Nitrate (µg/L)	45.6	64.3	65.5	66	85	87.5
3	Ammonia (µg/L)	178.76	151	134	216	211.5	211.5
4	Silica (µg/L)	11.75	12.5	11.6	15	17	21.5
5	pH	7.1	6	7.8	6.7	6.4	8.2
6	Temperature (^{0}C)	17	19	22	14.9	17	18
7	DO (mg/L)	8	6.5	7	10	7.5	8.5
8	Conductivity (µS/cm)	21	23	19.2	19	20.6	18

Table 4: Physicochemical parameters measured during dry and wet season in *Borale* Wetland

	Parameters	Dry Season			Wet Season		
		Plot A	Plot B	Plot C	Plot A	Plot B	Plot C
1	SRP (µg/L)	32.8	48.2	1	45.8	39.8	29.5
2	Nitrate(µg/L)	14.85	23	88.7	77.71	51.3	4.9
3	Ammonia(µg/L)	32.5	72.1	31.1	89.1	36.3	38.7
4	Silica (µg/L)	13.7	12.5	24.9	12.6	12.9	11.8
5	pH	8	8	7.1	8.6	8.6	7.7
6	Temperature (^{0}C)	19	18.9	17.7	17	15.1	16.6
7	DO (mg/L)	7.8	7	3.8	8.5	7.8	6
8	Conductivity (µS/cm)	70	88	82	76	85	78

3.2. Macroinvertebrate distribution in *Washa* and *Borale* Reserviors

The total number of macroinvertebrates collected in this study was 519 (in *Washa*) and 789 (in Borale). Eight families which belonged to three orders were recorded in *Washa* Reservoir (Table 5), whereas seven families belonging to four orders were recorded in *Borale* Reservoir (Table 6). Order Hemiptera was represented by 5 families, Coleptera by two and Ephemeroptera by one in *Washa* Reservior. Similarly, Hemiptera were represented by four families compared to other orders in *Borale* reservoir, whereas Coleptera, Tricoptera and Class Hirudinea were represented by one family each. Corixidae and Chironomidae comprised 64.5% of the total individuals in *Washa* Reservior (Figure 2), whereas Belostomatidae and Chironomidae comprised 90% in *Borale* Reservior (Figure 3). These results indicated a high dominance of the two pollution resistant families in both Washa and Borale reservoirs. This, in turn, showed the presence of higher pollution contaminants in both reservoirs. Pleidae, Veliidae, and Notonectidae were rarely (<5% each) observed in *Washa* while Philipotamidae, Velidae, Corixidae, and Leeches were rarely observed in *Borale* Reservior.

Among the identified families in *Washa* Reservior, seven of them were observed in Hab-Plot C (Table 7). Similarly, Corixidae and Chironomidae families were abundant in this site. . Belostomatidae was abundant at Hab-Plot C during the dry season. Nevertheless, Chironomidae was abundant at Hab-Plot A (Table 8).

Table 5: Macroinvertebrate family identified in *Washa* Wetland and their relative abundance

Family	Abundance (sum)	Relative abundance
Corixidae	227	0.451
Chironomidae	108	0.215
Haliplidae	48	0.095
Veliidae	16	0.032
Baetidae	42	0.083
Belostomatidae	37	0.074
Pleidae	19	0.038
Notonectids	6	0.012

Table 6: Macroinvertebrate family identified in *Borale* Wetland and their relative abundance

Family	Abundance	Relative abundance
Chironomidae	216	0.276
Belostomatidae	494	0.631
Philapotamidae	32	0.041
Corixidae	14	0.018
Notonectidae	19	0.024
Leeches	4	0.005
Velidae	4	0.005

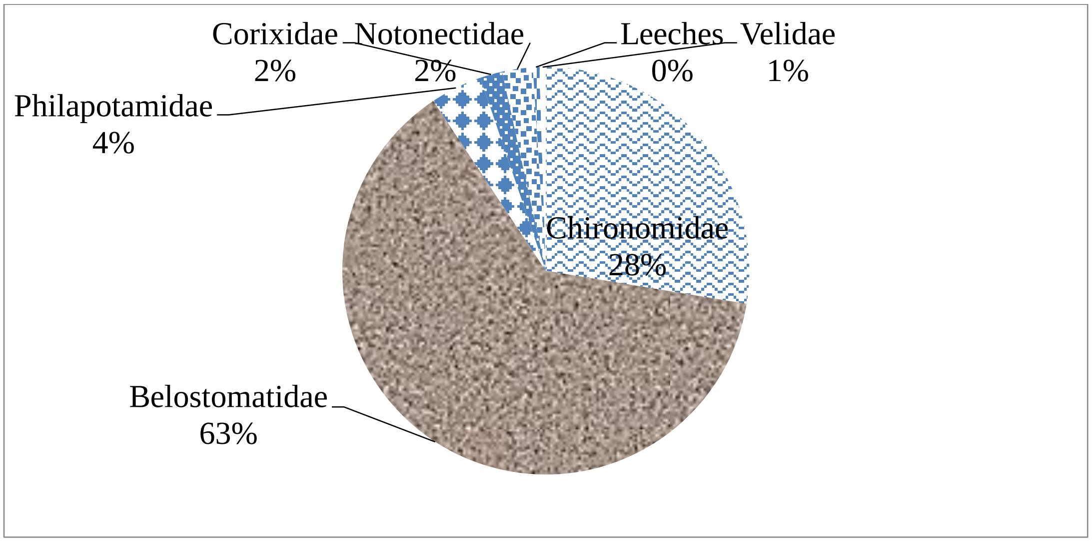

Figure 2: Macoinvertebrate families' percentage in *Wash* Wetland

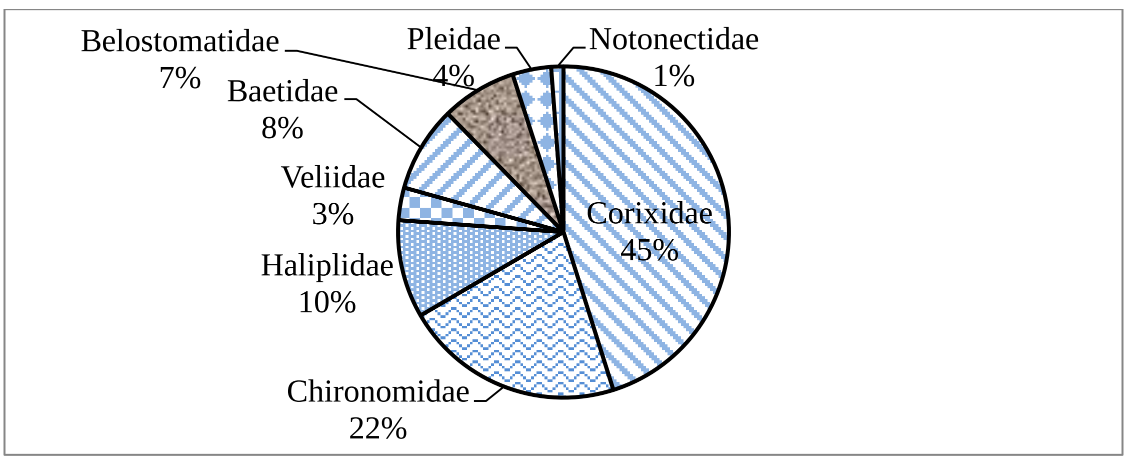

Figure 3: Macoinvertebrate families' percentage in *Borale* Wetland

Table 7: Abundance of macroinvertebrate families across the three plots in dry and wet seasons in *Washa* Reservoir

	Family	Dry Season			Wet Season		
		Plot A	Plot B	Plot C	Plot A	Plot B	Plot C
1	Chironomidae	57	26	5	77	46	5
2	Belostomatidae	18	92	137	28	82	13
3	Philapotamidae	4	2	0	14	12	0
4	Corixidae	2	0	0	12	0	0
5	Notonectidae	0	9	5	0	0	5
6	Leeches	0	2	0	0	2	0
7	Velidae	0	0	2	0	0	2

Table 8: Abundance of macroinvertebrate families across the three plots in dry and wet seasons in *Washa* Reservoir

	Family	Dry season			Wet season		
		Plot A	Plot B	Plot C	Plot A	Plot B	Plot C
1	Corixidae	27	8	82	35	10	65
2	Chironomidae	10	9	17	43	13	16
3	Haliplidae	6	5	6	10	0	21
4	Veliidae	6	0	0	10	0	0
5	Baetidae	0	3	11	0	5	23
6	Belostomatidae	0	10	1	0	23	3
7	Pleidae	0	14	5	0	0	0
8	Notonectids	0	0	6	0	0	0

4. DISCUSSION

Most of the measured physico-chemical parameters in this study revealed that both reservoirs had moderate water quality though there was spatial difference with respect to water quality among the sites. All the measured parameters in this study were found to be lower when compared to the same parameters in Koka Reservoir, except Ammonia (Habtamu, 2019) and Angrehb Reservoir except for DO (Alebachew, 2018).

The safe range of pH for drinking water is from 6.5 to 8.5 for domestic use and living organisms need (WHO, 2011). In this regard, it is fair to consider the mean pH level of both reservoirs if it serves the aforementioned purpose. DO level of *Washa* Reservoir is suitable for productivity of aquatic organisms more particularly for fish. Fish species such as *Cyprinus carpio* can survive in such environment as they can tolerate lower temperature. However, ammonia level was highest compared to the reservoirs mentioned, more particularly in *Washa* Reservoir. High level of ammonia in aquatic system is often an indication of fecal contamination (WHO, 2011). In this case, the water may be contaminated with fecal matter from nearby livestock. On the other hand, lower level of nitrate was recorded in both reservoirs compared to Angrheb and Koka Reservoirs. This indicated that the pollution extent of the two reservoirs' water was relatively low compared Angrheb and Koka reservoirs, but still there was pollution in Washa and Borale reservoirs, as there was high level of ammonia in the reservoirs. Hence, there were less abundant sensitive macroinvertebrate families.

Significant variation in SRP and ammonia concentration in Hab-Plot A site could be due to exposure to cattle and human interaction. However, a relatively stony edge (Dam) around Hab-Plot C might serve as buffer zone and could be the reason for lower level of the mentioned parameters. In *Borale* Reservior, cattle watering, agriculture practices, the absence of buffer, and high rate of siltation could contribute to lower oxygen level at Hab-Plot A. A lower oxygen concentration in a site ensures the presence of pollution resistant macroinvertebrate families.

The total number of macroinvertebrate individuals and taxa were much lower compared to similar other works (Ambelu *et al,* 2013; Alebachew, 2018; Yirga and Brook, 2019). Taxa richness is the measure of community's diversity and number of different families found in samples of each site. Reduction in community diversity is commonly associated with various forms of environmental pollution, including nutrient loading, toxic substances, and sedimentation (Yirga and Brook, 2019).

Reservoirs have generally a reduced diversity of benthic fauna as compared with natural lakes. Pamplin *et al*. (2010) observed the occurrence of few faunistic groups with low species number in each group and the majority of the species occurring with very low abundance in Americana Reservoir. In addition to the environmental degradation, the low abundance of insects in sediment of these reservoirs could be due to the preference of these organisms for free floating vegetation banks, especially *Eichhornia crassipes, Pistia stratiotes, Salvinia auriculata and Polygonum spp* (Tavares *et al*., 2004) which are absent in these reservoirs. These plants provide diversified habitats for macroinvertebrates, with wide food resources, breeding places and refugia (shelters) against predators.

The dominance of Hemiptera in these reservoirs indicated the presence of pollution as Hemipterans are relatively tolerant of many forms of pollution (Gooderham and Tysrlin, 2002). Both reservoirs were dominated by tolerant taxa such as Belostomatidae (10), Corixidae (9), and Chironomidae (8) which were good indicators of instability and highly modified with shoreline modification. With increased water pollution, some sensitive groups like EPT taxa will disappear being replaced by more hardy and tolerant groups (for example, Chironomids, Oligochaetes, Syrphidae) (Richard *et al*., 1997). The high percentage of a single or some common taxa at sites might be due to instability or high water-level fluctuation in the system. Sellam et al. (2017) also reported that the abundance of tolerant groups (Diptera, Chironomidae, and Hirudinea) increased with habitat disturbances.

5. CONCLUSIONS

Although most of the measured water quality parameters level was in the permissible range for both reservoirs, the concentration of ammonia was found to be at higher level than the normal range which indicated the presence of contamination in these reservoirs. There was also significant spatial variation in the reservoirs. The exposure of the plot sites to human intervention in the two reservoirs showed a relatively lower water quality whereas the relatively protected plot sites showed the opposite. The dominance of tolerant macroinvertebrate families and total absence of sensitive families indicated the presence of ecological instability and pollution in these systems. Hence, human interference and cattle drinking should be regulated before both systems are impaired permanently.

Conflict of interest

There is not any conflict of interests among authors and between authors and funding organization.

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Evaluation of Irrigation Water Quality of Woyito Irrigation Scheme at Bena Tsemay District in South Ethiopia in South Omo Zone, South Ethiopia

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ABSTRACT

Ethiopia's semi-arid agricultural land loses much of its productivity annually as a result of salinization and sodicity. Knowing the quality of irrigation water before using it for irrigation activities is crucial for land use and irrigation water management. This study was carried out to ascertain and categorize the quality of the irrigation water and suggest potential management alternatives in the south Ethiopian district of Bena Tsemay. To ascertain the quality of irrigation water utilized in the study area, a variety of analyses were performed on the collected water samples. These analyses included pH, EC, SAR, RSC, PI, Na%, and measurements of dissolved cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions ($SO4^{2-}$, HCO^{3-}, Cl^{-}, NO^{3-}, $PO4^{3-}$, and $CO3^{2-}$). The water under investigation had a pH between 8.05 and 8.48, which was slightly alkaline and ideal for irrigation. The EC was non-saline during the wet season and slightly to moderately saline during the dry season. The salinity of the area was exacerbated by extensive irrigation during dry seasons, which was partially alleviated by rainfall during wet seasons. During the wet season, the SAR was slightly to moderately sodic at 2.55 meq/l and 1.48 meq/l during the dry season, making it good for irrigation. The residual contained from wet to dry season sodium carbonate (0.36 to -1.02), potassium ion (0.1 to 0.31), and sodium ion (2.73 to 2.07) meq/l, respectively. Besides, chloride (0.31meq/l) level was appropriate for irrigation. A classification of slight to moderate pollution was observed in the HCO3 of the water. The results indicated that the concentrations of phosphate (0.32 meq/L), sulfate (0.26 meq/L), and nitrate (0.4 meq/L) in the water were within acceptable limits, making it suitable for irrigation. To address the long-term salinity and sodicity issues in the research area, salinity and sodicity management and control strategies were employed.

Keywords: Irrigation practices, water quality, Woyito irrigation scheme, salinity problem, sodium adsorption ratio

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1. INTRODUCTION

In order to meet the growing food needs of the world's population, irrigation practices are crucial to increase agricultural productivity and production. Rivers and streams are water resources that cross borders and provide water for agriculture. However, irrigated agriculture is only associated with the physical availability of water, while the quality of water for sustainable agricultural production is often disregarded (Molla & Fitsume, 2017). Soil quality, one of the most important subsystems of agricultural land, changes over time owing to changes in the environment or management practices (Hailu, Wogi, & Tamiru, 2020). Salinization is one of the most devastating environmental pressures resulting from improper irrigation management, leading to a significant reduction in cropland productivity and crop quality (Shahbaz & Ashraf, 2013).

Saline regions of Ethiopia, characterized by higher evapotranspiration in relation to precipitation, are located in the Rift Valley, arid, and semi-arid lowlands. Because of the salinity of the soil and water, arid and semi-arid agro-ecologies, which account for around 50% of the country's geographical area, are considered to be marginal conditions for agricultural development. Low annual rainfall and high daytime temperatures in these lowland areas led to high water evaporation and high concentrations of soluble salts (Begizew, 2021).

Salinization is a problem for irrigated agricultural land owing to the improper management of irrigation systems and poor quality of irrigation water. Ethiopia ranked seventh in the world in terms of the proportion of land area affected by salinization (Giday Adhanom, 2019). In the Rift Valley, large-scale irrigation projects were developed without adequate drainage systems to control salinity. This led to a rapid and sharp increase in salinity and soil salinization and eventually to the loss of land suitable for arable farming in these areas (Walche, Haile, Kiflu, & Tsegaye, 2023).

The main causes of soil salinization in the lowland areas of Ethiopia include: poor water management techniques on farms, intensive soil irrigation, use of poor quality water, and lack of adequate drainage infrastructure (Gebremeskel et al., 2018). As salts alter the osmotic link between soil moisture and roots, they are the main cause of crop problems in poor water quality (Machado & Serralheiro, 2017). Irrigation water must not only be free of chemical and biological contaminants but also contain the right amount of salt. Irrigation water with a high salt content inhibits plant growth and alters the permeability, structure, and aeration of the soil (Singh, Mahato, Neogi, & Singh, 2010); Ackah et al., 2011)).

Reduction of turgor pressure, slowing of cell expansion, and damage to chloroplasts are the effects associated with salt-water irrigation which, in turn, affects growth rate and photosynthesis. Crop yield and dry matter accumulation are ultimately affected by these changes. Malash, Flowers, & Ragab, 2005 reported that gradual increase in soil salinity occurs when saline water is constantly used for irrigation. The intricate relationship between soil systems and water is controlled by the chemical exchange process between the two media (Molla & Fitsume, 2017).

Assessing and testing water quality is an important task especially when the water is used for irrigation purposes. The study area, the Woyito irrigation system, is characterized by an arid and semi-arid climate with low rainfall. Therefore, the communities surrounding the irrigation system rely heavily on conventional furrow and flood irrigation techniques. This has led to salinity and sodicity hazards occurring on farms. However, the salinity of irrigation water in the study area was not recorded in the past, making it difficult to develop intervention scenarios. Farmers are not aware of the salinity of irrigation water or the causes of flooding in these areas. The aim of this study is therefore to assess the quality of irrigation water used in the area and provide baseline data for the irrigation system.

2. MATERIALS AND METHODS

2.1. Study Area Description

2.1.1. Location

The study was conducted in the Bena Tsemay District of South Omo Zone, Southern Ethiopia. The research area is situated at 660 meters above sea level at a latitude of 5°18′0″ to 5°31′33″ N and a longitude of 36°52′30″ to 37°5′0″ E (Figure 1). The region is located in the eastern part of the Bena Tsemay District, 82 kilometers from Jinka, 438 kilometers from Hawassa, and 668 kilometers from Addis Abeba. The area is topographically characterized by valleys, wide flatlands, arid terrain, and a meandering river that stretches to the Chew Bahir area.

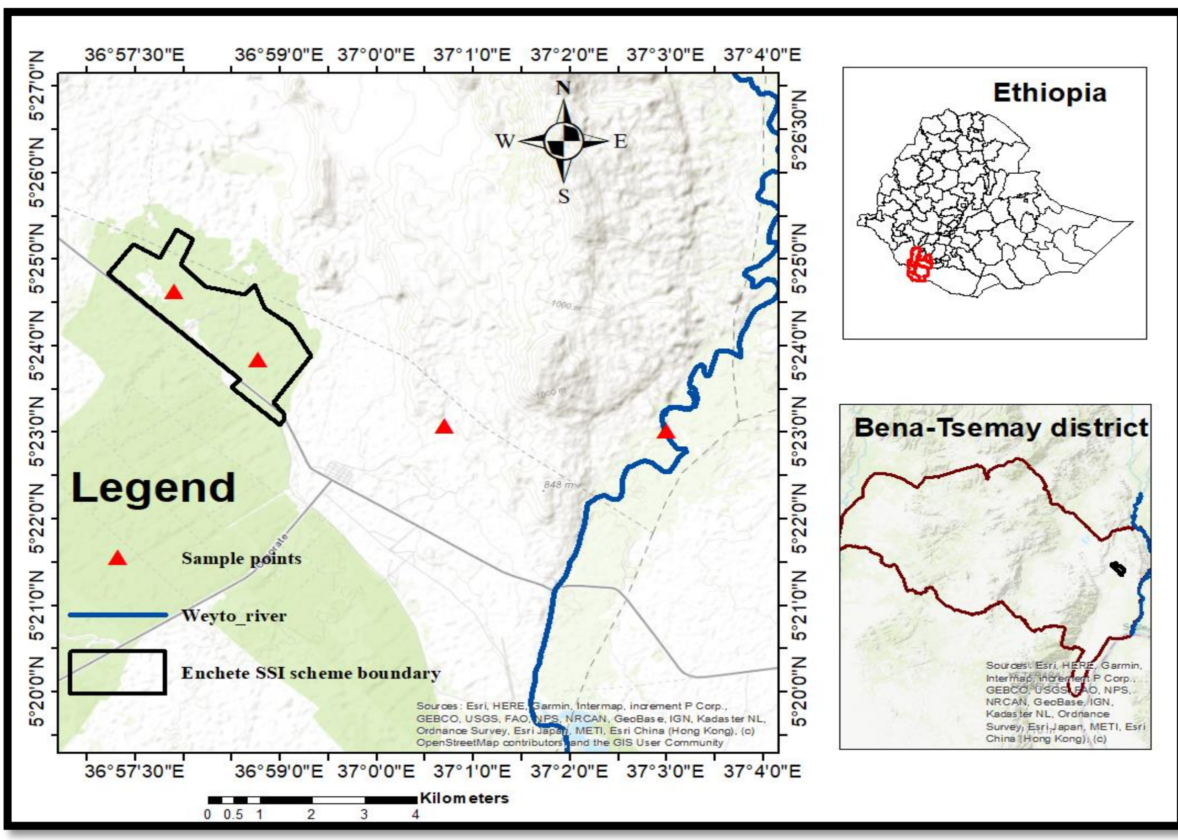

Figure 1: The study area's location map

2.1.2. Climate and Hydrology

The research area had average annual rainfall ranging from 200 to 578 mm and average annual temperature between 25°C and 40°C (Figure 2**: Mean monthly rainfall and temperature of the study area (2022 and 2023)**). The Woyito River served as a source for irrigation. It flows from north to south with its outflow into Chew Bahir Wetlands. Besides, the present study area lies within southern part of the Rift Valley Drainage system (Bezabih Bashe, 2017).

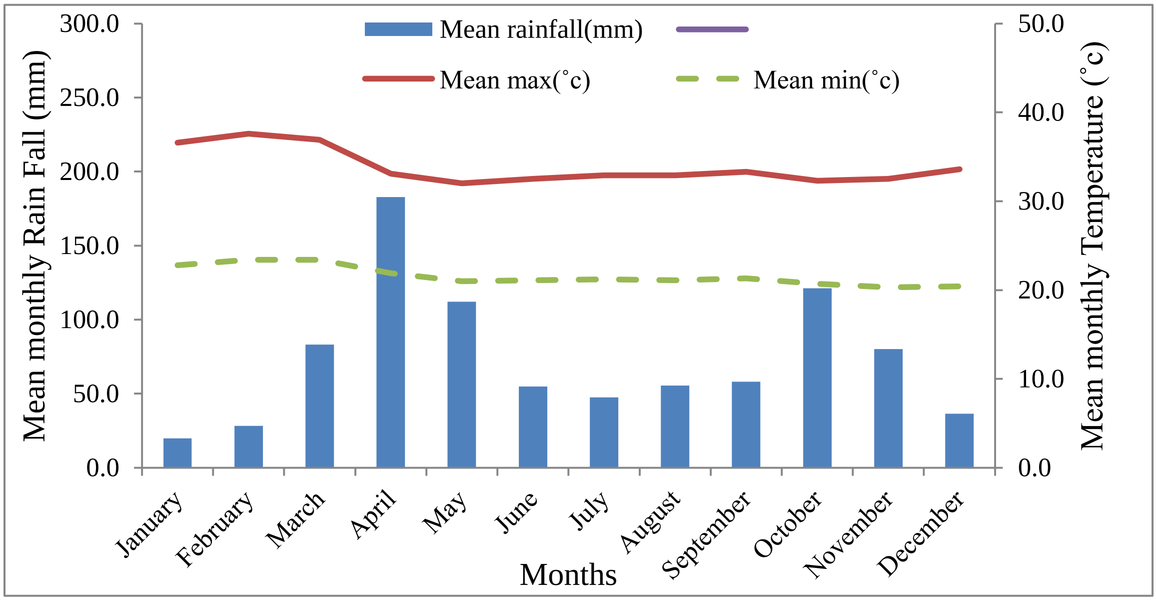

Figure 2: Mean monthly rainfall and temperature of the study area (2022 and 2023)

2.1.3. Land use land cover situation of the area

The Woyito Watershed land use and land cover (LULC) constituted sand, bodies of water, hillsides, bare soils, forests, or other vegetation, dry river beds (DRB), and agricultural land (Bezabih Bashe, 2017). Irrigable agricultural land is the main type of land use that dominates the study area. The soil in the study area was texturally classified as loam soil (Mugoro, Assefa, & Getahun, 2020). The most important irrigated crops of the study area included: cotton, sesame, maize, sorghum, onions, tomatoes, bananas, peppers, watermelon, and sunflowers.

2.2. Water Sampling and Analysis

2.2.1. Site selection

To identify the representative sites, a reconnaissance survey and field observation were conducted in the farm from upstream to downstream along the proposed plan. The sampling locations provided typical water quality; samples along the length of the canal were chosen based on road access to the area being studied. Using purposive sampling method, the sampling sites were chosen from the upper, middle, and lower course of the Woyito irrigation scheme in 2022 during dry and wet seasons.

2.2.2. Sampling technique

In accordance with the requirements of US Salinity Laboratory (McGeorge, 1954), the irrigation water samples were collected and processed. The water samples were collected during the morning hours and subsequently dispatched to the laboratory for analysis within a 24-hour. A one-liter plastic bottle that had been properly washed with distilled water was used to collect irrigation water samples from four typical sites in a single day. The water samples that were taken were promptly sealed to prevent air exposure and subjected to sensitive parameter analysis right away.

2.2.3. Sample collection

In order to test the water quality of the irrigation, representative samples were taken throughout the wet and dry seasons depending on the state of the river flow. Water samples were collected from the upper, middle, and lower irrigation schemes (Enchete and Duma). In order to classify the quality of irrigation water, the collected water samples were analyzed by various parameters in the laboratory of the Arba Minch University Water Technology Institute. Accordingly, the parameters for analyzing irrigation water included: pH, EC, soluble cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), soluble anions ($Cl^{-}SO_4^{2-}$, HCO_3^{-}, and CO_3^{2-}).

2.2.4. Laboratory analysis

The pH and EC of irrigation water were measured with a multi-meter devise (Seyedsadr et al., 2022). A flame-photometer was used to measure the soluble Na^{+} and K^{+} (Banerjee &

Prasad, 2020), while an EDTA titrimetric method was used to measure the soluble Ca^{+2} and Mg^{+2} (Barrows & Simpson, 1962) . The volumetric titration method was utilized to determine the total alkalinity as carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) (Verma, 2004). The sulfate (SO_4^{2-}) was examined using a UV-vis spectrophotometer and the turbid metric method (Morais, Rangel, & Souto, 2001). The silver nitrate titrimetric method was used to determine the amount of chloride in the sample (Kolthoff & Kuroda, 1951). Ascorbic acid and disulphonic acid methods were used to determine phosphate and nitrate with a UV-vis spectrophotometer (O, Ruth, Jane, & Charles, 2013). .

The amounts and concentrations of the different chemical properties analyzed were used to compute the SAR, Na%, PI, and RSC of the water samples. , SAR, Na%, and PI are the most fundamental metrics used to assess levels of sodium and associated risks to crops (Chidambaram te al., 2022). Based on measured values of Na^+, K^+, Ca^{2+}, and Mg^{2+}, the following formulas were used to determine sodium adsorption ratio (SAR), sodium percentage (%Na), and permeability index (PI) in the irrigation water. Residual sodium carbonate (RSC) was calculated using concentrations of HCO_3^- and CO_3^{2-} in relation to Ca^{2+} and Mg^{2+}:

$$SAR = \frac{Na^+}{\sqrt{\left(\frac{Ca^{2+}+Mg^{2+}}{2}\right)}} \quad (1)$$

$$Na\% = \frac{Na^+ + K^+}{Ca^{2+}+Mg^{2+}+Na^+ + K^+} * 100 \quad (2)$$

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+}+Mg^{2+}+Na^+} * 100 \quad (3)$$

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (4)$$

For the concentrations of cations and anions in equations 1- 4, all measurements were expressed in milliequivalents per liter, or meq/L.

The standards outlined in Table 1 were used to assess the water quality suitable for irrigation. The useful suggestions were applied successfully to evaluate common components of water resources in irrigated agriculture. Although the criteria were good to start when identifying restrictions on water quality, they were not sufficient by themselves. Adaptations or solutions to these constraints were also needed (Ayers & Westcot, 1985). Symbols, rules, and laboratory computations and determinations were listed below.

Table 1: Irrigation water quality interpretation guideline from Ayers & Westcott (1985); (Eaton 1950; Wilcox et al. 1954) and Bauder et al., (2011)

Irrigation water quality parameter				Classification		
				None	Slight to Moderate	Severe
EC				< 0.7	0.7 – 3.0	> 3.0
SAR	=	0 – 3	and ECw =	> 0.7	0.7 – 0.2	< 0.2
	=	3 – 6	=	> 1.2	1.2 – 0.3	< 0.3
	=	6 – 12	=	> 1.9	1.9 – 0.5	< 0.5
	=	12 – 20	=	> 2.9	2.9 –1.3	< 1.3
	=	20 – 40	=	> 5.0	5.0 – 2.9	< 2.9
Cl^-(meq/l)				< 4.0	4 – 10	> 10
$NO3^-$(mg/l)				< 5	5 – 30	> 30
$HCO3^-$(meq/l)				< 1.5	1.5 – 8.5	> 8.5
pH				acidic	normal range	Basic
				< 7	6.5 – 8.4	> 7
RSC(meq/l)				Safe	Marginal	Unsuitable
				< 1.25	1.25 – 2.50	> 2.5

2.2.5. Statistical analysis

Water quality data from the Woyito Irrigation Scheme were categorized according to seasonal variations. For each parameter and sampling site, the mean and standard deviation of water quality data were computed.

3. RESULTS AND DISCUSSION

3.1. Characteristic features of irrigation water quality

A chemical composition analysis was conducted on irrigation water samples obtained from the Woito Irrigation Scheme (Tables 2 and 3). The intended use of the water determines its quality. For irrigation water, standard quality requirements include salinity, sodicity, and ion toxicities. The soluble salt concentration in irrigation water is commonly measured regarding electrical conductivity (EC) and pH (Abdurahman, Shure, & Wakshum, 2017).

3.2. The pH of Water Sample

The average pH value of the Woyito Irrigation Scheme ranged between 8.05 and 8.48 during wet and dry seasons (Table 2: **The chemical composition of samples from irrigation water during the wet season** and **Table 3: The chemical composition of sample irrigation water during the dry season** , Figure 3**: Mean seasonal variation of irrigation water quality parameters in the area**). The water samples from the Woyito Irrigation System had a high pH value. According to (Haile, 2019) and (Bauder, Waskorn, & Davis, 2011), this was due to high bicarbonate and carbonate levels. The pH of the Woyito Irrigation water remained within an acceptable range for each season (Aregahegn & Zerihun, 2021). Similarly, water with a pH of 6.0 to 8.5 is often acceptable for irrigation (Armstrong, Cotching, & Bastick, 2001). The pH of irrigation water can be affected by the soil to which it is applied and is therefore not considered an absolute indicator of water quality; furthermore, most crops can tolerate a wide range of pH values (Rengasamy, 2018).

3.3. Salinity (EC) of Irrigation Water

The salt content is a decisive parameter for the quality of irrigation water as it is directly proportional to the amount of salt dissolved in the water. The concentrations of soluble salts in irrigation water can be classified on the basis of the electrical conductivity of the water (ECw). The salinity hazard in irrigation water was classified based on the EC values as indicated in Table 2: **The chemical composition of samples from irrigation water during the wet season** and **Table 3: The chemical composition of sample irrigation water during the dry season** , Figure 3**: Mean seasonal variation of irrigation water quality parameters in the area**. The EC value of irrigation water was classified on the basis of the FAO guidelines (Ayers & Westcot, 1985). EC value of irrigation water in the study area ranged from 0.29 to 0.3 in the wet season with an average of 0.3dS/m. In the dry season, the electrical conductivity (EC) ranged between 1.84 and 1.88 with an average of 1.87dS/m. According to (Ayers &

Westcot, 1985), the EC value of the Woyito Irrigation water was classified as non-saline in the wet season and slightly to moderately saline in the dry season.

The analysis of the water samples revealed seasonal fluctuations in the electrical conductivity of the irrigation water. The lower values observed in the wet season and higher values in the dry season can be attributed to salt leaching caused by rainfall (Lu et al., 2015). In the dry season, irrigation water evaporates due to high evaporation rates, while soluble salts accumulate on the soil surface (Begizew, 2021). According to (Aregahegn & Zerihun, 2021), the concentration of dissolved salts is high in the dry season when the river level decreases, and lowest in the wet season when the water level increases. In arid and semi-arid regions, poor drainage can cause or exacerbate salinization (Yasuor, Yermiyahu, & Ben-Gal, 2020). A very dense soil structure with insufficient water infiltration, inadequate aeration, and increased surface crusting is the result of continuous irrigation with excessively salinized water. This leads to a sodium hazard that hinders seedling emergence and root growth; moreover it makes tillage difficult (Zaman et al., 2018).

3.4. Sodicity (SAR) of Irrigation Water

The sodium content of irrigation water is crucial for assessing its potential hazard and is usually evaluated using the sodium adsorption ratio (SAR). The SAR is an important indicator of sodium hazards to plants and soil structure and helps determine the suitability of the water for irrigation purposes. This hazard is due to the negative effects of salt on the soil. The SAR value of irrigation water is categorized based on the irrigation water quality guidelines listed in **Table 1**. During the wet season, the SAR of irrigation water in the study area ranged from 2.48 to 2.68 with an average of 2.55meq/l as shown in Table 2: **The chemical composition of samples from irrigation water during the wet season** and **Table 3: The chemical composition of sample irrigation water during the dry season** , and on **Figure 3: Mean seasonal variation of irrigation water quality parameters in the area**. In the dry season, the SAR ranged from 1.44 to 1.55 with an average of 1.48meq/l. Hence, the SAR of irrigation water in the study area was suitable for irrigation in the dry season, while it was slightly-moderately suitable for irrigation in the wet season as indicated in **Table 1**. While low-sodium water is safe for irrigation, it can harm plants such as fruit trees and avocados that are sensitive to sodium (Zaman et al., 2018). Gypsum is an important chemical additive used to neutralize the RSC of irrigation water and is the most cost-effective alternative to reduce the sodium content of irrigation water compared to other additives (Chander, Rajender, Yadav, & Chander, 2019).

3.5. Residual Sodium Carbonates (RSC)

The RSC (Residual Sodium Carbonate) value is a measure of the alkalinity of the irrigation water, which consists of HCO_3^- and CO_3^{2-} ions in relation to Ca^{++} and Mg^{++} ions. If there is an excess of carbonates in the irrigation water, the sodium ions dominate as carbonates can form precipitates with calcium and magnesium ions (Nagaraju, Sunil Kumar, & Thejaswi, 2014). The RSC values determined in the wet season ranged between 0.26 and 0.45meq/l with an average value of 0.36meq/l as indicated in Table 2: **The chemical composition of samples from irrigation water during the wet season** and **Table 3: The chemical composition of sample irrigation water during the dry season** . In the dry season, the values ranged from -1.21 to -0.90meq/l with an average value of -1.02meq/l. The analysis showed that the mean RSC value of the water samples from the Woyito Irrigation Scheme was less than 1.25meq/l and was suitable for irrigation (Ayers & Westcot, 1989; Eaton, 1950; Wilcox, Blair, & Bower, 1954).

Table 2: The chemical composition of samples from irrigation water during the wet season

Sampling Point	pH	EC	Soluble Cations (meq/l)				SAR	Soluble anions (meq/l)						RSC	PI	Na%
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}		$HCO3^{-}$	$CO3^{2-}$	Cl^{-}	$S04^{2-}$	$PO4^{3-}$	$NO3^{-}$			
S1	8.10	0.30	1.32	0.89	2.61	0.11	2.48	2.39	0.27	0.28	0.26	0.32	0.63	0.45	86.17	55.15
S2	8.10	0.29	1.32	1.01	2.71	0.10	2.51	2.33	0.27	0.31	0.26	0.33	0.21	0.26	83.95	54.58
S3	8.00	0.29	1.36	0.97	2.74	0.09	2.54	2.49	0.27	0.33	0.27	0.28	0.29	0.42	85.10	54.87
S4	8.00	0.30	1.32	0.97	2.87	0.10	2.68	2.37	0.25	0.33	0.25	0.35	0.47	0.33	85.36	56.39
Mean	8.05	0.30	1.33	0.96	2.73	0.10	2.55	2.39	0.26	0.31	0.26	0.32	0.40	0.36	85.15	55.25
Min	8.00	0.29	1.32	0.89	2.61	0.09	2.48	2.33	0.25	0.28	0.25	0.28	0.21	0.26	83.95	54.58
Max	8.10	0.30	1.36	1.01	2.87	0.11	2.68	2.49	0.27	0.33	0.27	0.35	0.63	0.45	86.17	56.39
SD	0.06	0.01	0.02	0.05	0.11	0.01	0.09	0.07	0.01	0.03	0.01	0.03	0.19	0.09	0.92	0.80

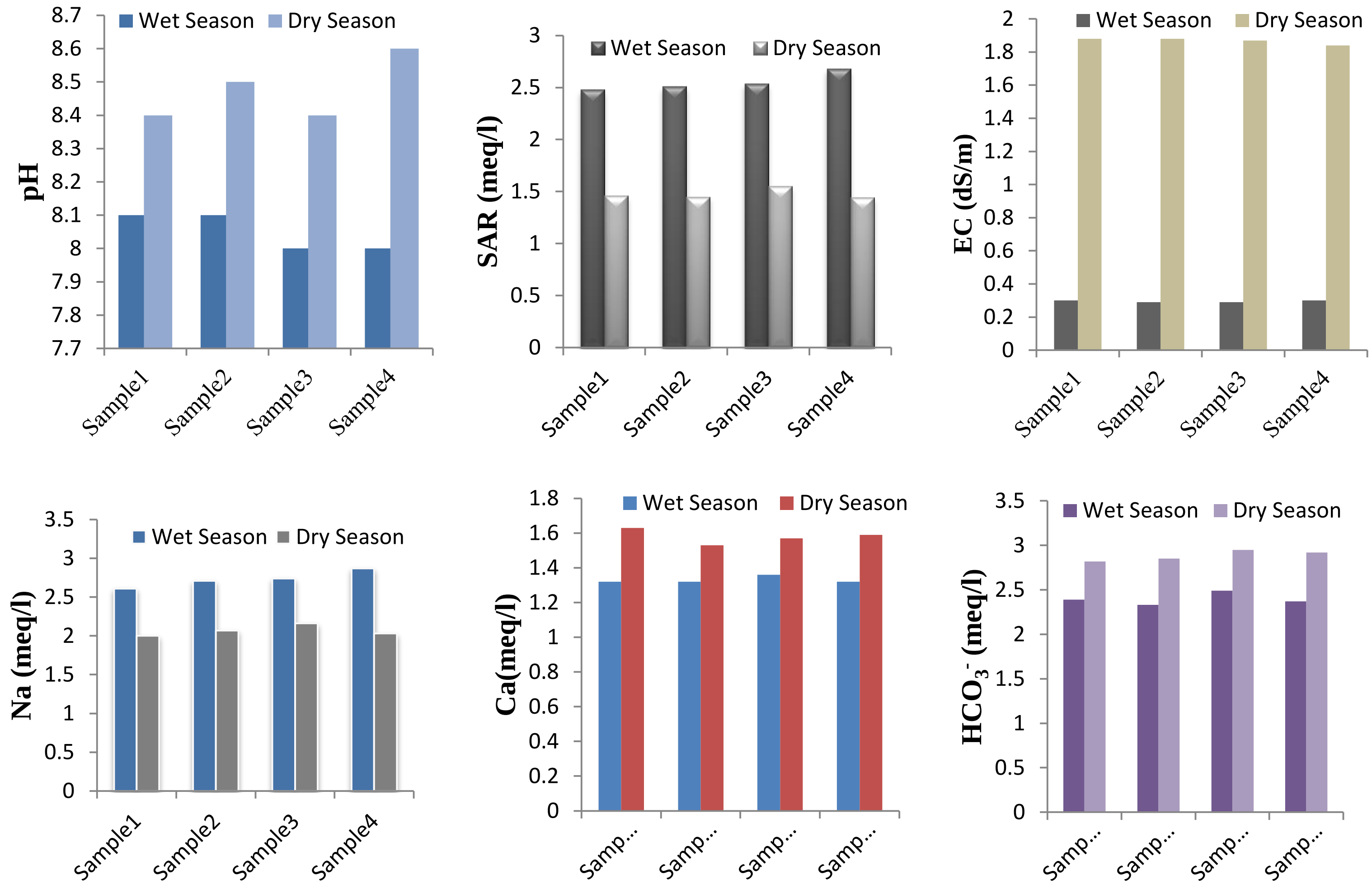

Figure 3: Mean seasonal variation of irrigation water quality parameters in the area

3.6. Concentration of Soluble Cations in Irrigation Water

Higher concentrations of sodium (Na) ions in irrigation water or on agricultural land are particularly concern to the Woyito irrigation scheme users, due to its toxicity to plants and the adverse effects on soil physical properties. Excessive sodium can lead to soil compaction, reduced permeability, and poor aeration, hindering plant growth and crop yield. Sodium toxicity can show up on plants in the form of leaf burns, scorching, and dead tissue on the outer edges of leaves (Simsek & Gunduz, 2007).

The sodium ion value ranged from 2.00 to 2.16meq/l with an average value of 2.07meq/l and 2.61 to 2.87meq/l with an average value of 2.73meq/l in the dry and wet seasons, respectively. The result for Na in (Tables 2 and 3, Figure 3) was less than 20meq/l and the water was suitable for irrigation (Ayers & Westcot, 1985). The potassium ion value ranged from 0.09 to 0.11meq/l with an average value of 0.10meq/l and 0.30 to 0.33meq/l with an average value of 0.31meq/l in the wet and dry seasons, respectively. Therefore, irrigation water with a potassium ion concentration of less than 2 meq/l in Tables 2 and 3 was suitable for irrigation. The variations in Na^+ and K^+ concentrations may be related to the geological composition or mineral makeup of the locations.

The calcium ion value ranged from 1.32 to 1.36meq/l with an average value of 1.33meq/l and 1.53 to 1.63meq/l with an average value of 1.58meq/l in the wet and dry seasons, respectively. Hence, the calcium ion concentration in irrigation water as indicated in (Table 2 and **Table 3**, **Figure 3: Mean seasonal variation of irrigation water quality parameters in the area**) was below 20meq/l and was suitable for irrigation. The magnesium ion value ranged from 0.89 to 1.01 meq/l with an average value of 0.96meq/l and 2.13 to 2.53meq/l with an average value of 2.33meq/l in the wet and dry seasons, respectively. As a result, the magnesium ion concentration in irrigation water shown in Tables 2 and 3 was below 5meq/l, which was suitable for irrigation (Ayers & Westcot, 1985). , There was an observed increase in the levels of Ca^{2+} and Mg^{2+}during the dry season. This trend may be attributable to the rapid ingress of rainwater which curtails the dissolution of soil minerals and rocks (Al-Khashman, 2008).

The sodium content (Na %) is an important factor that determines the suitability of irrigation water. A higher concentration of Na^+ leads to chemical bonding with the soil and reduces water movement capacity (Ayers & Westcot, 1985). The values for sodium content (Na %) ranged from 60.77 to 63.08 with a mean of 62.19 in the dry season and from 43.61 to 45.42 with a mean of 44.75 in the wet season. The slight decrease in sodium during the wet season was due to the dilution caused by rainwater; whereas evaporation contributes to ion concentration throughout the dry season (Tlili-Zrelli, Gueddari, & Bouhlila, 2018). The Na% value of irrigation water in the study area was moderately suitable for irrigation in the wet season (Chidambaram et al., 2022). The low quality of irrigation water with Na% value more than 50% was observed in the dry season (Berhanu, Hatiye, & Lohani, 2023).

The permeability index (PI) was used to determine the ability to move water in soil based on the concentration of Ca^{2+}, Mg^{2+}, Na^+ and HCO_3^-. The PI values varied between 83.95 and 86.17 with a mean value of 85.15 in the wet season while the PI value in the dry season ranged between 61.30 and 64.51 with a mean value of 63.03. Seasonal variation of permeability index is mainly related to dilution in the wet season, evaporation throughout the dry season, and agricultural activities (Tlili-Zrelli et al., 2018). The total PI value in both seasons showed a low quality of irrigation water with a PI of more than 60 (Berhanu et al., 2023).

3.7. Concentration of Soluble Anions in Irrigation Water

The most common plant toxicity is caused by chloride ions in irrigation water. Chlorides are necessary for plant growth, but in high concentrations can inhibit plant growth and be highly toxic to sensitive plants, leading to leaf tissue diseases (Simsek & Gunduz, 2007). The chloride ion value was between 0.28 and 0.33meq/l with an average value of 0.31meq/l during the wet season. Hence, irrigation water with a chloride concentration of less than 2meq/l as indicated in Table 2 is safe for all plants (Bhatt et al., 2023; Bauder et al., 2011).

The concentration of bicarbonate ion varied between 2.33 and 2.49meq/l with an average value of 2.39meq/l and between 2.82 and 2.95meq/l with an average value of 2.88meq/l in the wet and dry seasons, respectively. Thus, the concentration of bicarbonate ion in the irrigation water as in Table 2, **Table 3**, and **Figure 3** was between 1.5 and 8.5meq/l. As a result, the irrigation water in the study area was classified as slightly to moderately suitable for irrigation (**Table 1**). The standard deviation (SD) showed that least variability of HCO_3^- in the Woyito Irrigation. However, the HCO_3^- value in the study area did not vary significantly during the study seasons.

The concentration of carbonate ion in the water sample varied between 0.25 and 0.27meq/l with an average value of 0.26meq/l and 0.00meq/l in the wet and dry seasons, respectively (Table 2 and **Table 3**). In general, the concentration of carbonate ion in the irrigation water was below 0.1meq/l in the dry season, which is suitable for irrigation(Ayers & Westcot, 1985). Calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) precipitate insolubly because of carbonate ($CO3_2^-$) and bicarbonate (HCO_3^-) concentration in irrigation water (Zaman et al., 2018).

The nitrogen source refers to the required amount of nitrate used as fertilizer to promote plant growth. The nitrogen source is the required amount of nitrate used as fertilizer for plants. However, excessive amounts can lead to untimely growth or unsightly deposits on the fruits, delayed plant maturity, and yield reduction (Simsek & Gunduz, 2007; Ahmed et al., 2020). These problems were associated with proper fertilization and excellent irrigation management (Shaviv & Mikkelsen, 1993; Simsek & Gunduz, 2007 and Ahmed et al., 2020). The value of nitrate concentration ranged from 0.21 to 0.63 mg/l with an average value of 0.40 mg/l during the wet season. Nitrate content in the area was less than 5 mg/l, indicating that nitrates as fertilizers may be appropriate in certain cases. It is important to exercise caution and use fertilizers responsibly owing to their potential environmental impacts.

The concentration of phosphate ion varied between 0.28 and 0.35 mg/l with an average value of 0.31 mg/l during the wet season. Hence, the phosphate value of irrigation water in the study area was less than 2 mg/l, which was suitable for irrigation (Ayers & Westcot, 1985). The slight seasonal variation observed resulted from the accumulation of phosphates from anthropogenic activities such as agricultural practices and domestic waste discharge which may have harmful impact on the environment. The concentration of sulfate ion varied between 0.25 and 0.27meq/l with an average value of 0.26meq/l during the wet season. Thus, the sulfate value of irrigation water in the study area was below 20meq/l, which is suitable for irrigation (Ayers & Westcot, 1985)

Table 3: The chemical composition of sample irrigation water during the dry season

Sampling Point	pH	EC	Soluble Cations (meq/l)				SAR	Soluble anions (meq/l)		RSC	PI	Na%
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}		HCO_3^-	CO_3^{2-}			
S1	8.40	1.88	1.63	2.13	2.00	0.30	1.46	2.82	0.00	-0.94	63.92	38.04
S2	8.50	1.88	1.53	2.53	2.07	0.31	1.45	2.85	0.00	-1.21	61.30	36.92
S3	8.40	1.87	1.57	2.28	2.16	0.33	1.55	2.95	0.00	-0.90	64.51	39.23
S4	8.60	1.84	1.59	2.37	2.03	0.30	1.44	2.92	0.00	-1.04	62.40	37.07
Mean	8.48	1.87	1.58	2.33	2.07	0.31	1.48	2.88	0.00	-1.02	63.03	37.81
Min	8.40	1.84	1.53	2.13	2.00	0.30	1.44	2.82	0.00	-1.21	61.30	36.92
Max	8.60	1.88	1.63	2.53	2.16	0.33	1.55	2.95	0.00	-0.90	64.51	39.23
SD	0.1	0.02	0.04	0.17	0.07	0.01	0.05	0.06	0	0.139	1.456	1.065

4. CONCLUSION AND RECOMMENDATIONS

4.1. Conclusion

Irrigation water quality parameters such as pH, EC, SAR, RSC, PI, Na%, dissolved cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), and anions (SO_4^{2-}, HCO_3^-, Cl^-, NO_3^-, $PO4_3^-$, and CO_3^{2-}) were important measures for the assessment of irrigation water quality in the studied area. The results of the study showed that the pH value of the water samples was below the permissible limit. The EC value of the irrigation water was classified as non-salty in the wet season and slightly-moderately salty in the dry season.

The SAR value of irrigation water affects crop production by increasing the risk of salinity. The SAR was low and suitable in the dry season, while it was moderately suitable in the wet season. However, this resulted in increased soil erosion, lower crop yield, and reduced soil permeability. Therefore, it is important to monitor the quality of irrigation water to minimize adverse effects especially in the wet season.

According to the analysis, the water samples from the Woyito Irrigation System had a mean RSC value of less than 1.25meq/l, indicating that the water was appropriate for irrigation. The water was appropriate for irrigation since the Na ion value was less than 20meq/l and the potassium ion was less than 2meq/l. All plants are safe since the amount of chloride ions in irrigation water was less than 2meq/l. The irrigation water was classified as slightly to moderately suitable for irrigation based on its bicarbonate ion concentration. Besides, the values of nitrate, phosphate, and sulfate were suitable for irrigation. The results from water quality and soil analyses showed that salinity and sodicity were major problems.

4.2. Recommendations

Therefore, to lessen the impact of long-term salinity and sodicity hazard in the study area, proper salinity and sodicity management and control measures should be used. These measures include: adequate drainage, blending low-quality irrigation water with high-quality water, application of mineral amendments, and planting more salt-tolerant crops.

In dry and semi-arid areas, surface irrigation technique such as flood, basin, furrow, and border, were typically exposed to high evaporation rates, which raised the salt concentration in the water. As a result, pipe systems may help to regulate the salinity risks of water resources by substituting open irrigation canals. As a result, more research should be done to ascertain the condition of groundwater quality in the research area.

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Ethiopia: An Emerging Renewable Energy Power Hub of Africa

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ABSTRACT

This study examines the emergence of Ethiopia as a renewable energy power hub in Africa by analyzing trends, patterns, changes, and continuities in the development of hydropower. Methodologically, the study used a qualitative research approach supported by a historical and geopolitical lens. The data used in this study was collected from 50 key informants from government institutions, regional organizations, academic institutions, research institutes, power sector advisors, and independent consultants. The study identifies three interrelated and mutually reinforcing factors that contribute to the repositioning of Ethiopia as an emerging renewable energy power hub of Africa. The vast renewable energy potential, water-based development attempts across successive regimes, and the booming of hydropower have transformed hydropower potential into 'real power' since 2000. The strategic location of the country specifically its hydrological, geological, and topographical characteristics have enabled the country to become a powerhouse and battery of the Horn of Africa. Additionally, the massive post-2000 hydropower development has simultaneously made the country heavily dependent on its hydropower as it generates more than 90 percent of the electricity from water. The study identified four patterns from hydropower development: the entanglement of domestic and international politics as the underlying factor for the country’s hydropower development, the strong correlation between political stability and hydropower development, the role of hydropower in foreign policy orientation and power balance, and the state-led nature of hydropower development. The study also find outs common barriers to hydropower development across the hydropower epochs, including the transboundary nature of the rivers, geopolitical factors, lack of finance, climate change, and political instability. Overall, the study reveals how Ethiopia's unique position combines abundant hydropower resources, development ambition, and strategic planning, allowing the country to become a major player and actor in the emerging world order that heavily relies upon renewable and green energy resources.

Keywords: Ethiopia, hydropower, renewable energy, hydropower potential

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INTRODUCTION

Ethiopia has the largest hydropower potential (45,000 MW) in Africa, which is the second largest next to the Democratic Republic of Congo (Ethiopian Electric Power Corporation [EEPCo], 2014; International Hydropower Association [IHA], 2018; Ashebir, 2022; Dereje *et al.*, 2011). In addition, the country has unique geographical, topographical, geological, and climatic features that are ideal for exploiting its hydropower potential. However, the development of hydropower since1912 has undergone a slow process until it boomed with the turn of the millennium.

Before 1991, the total installed capacity was 370 MW (EEP, 2017:3). Hydropower projects constructed during this period included Aba Samuel, Koka, Ourso, Tis Abbay, Awash I and II, Fincha and Melka Wakena. In the post-1991 period, however, hydropower entered its booming period owing to the construction of large-scale hydropower projects such as Tekeze, Gilgel Gibe I, Gibe II, Gibe III, Beles, Amerti Neshi, Genale Dawa III, GERD and Koyisha. With this hydropower development, the total installed capacity of the country was raised from around 370 MW in 1991 to 5, 256.5 MW in 2023 (Ethiopia Electric Power [EEP], 2023:11). Of the installed capacity, 4,820.2 MW came from hydropower sources (EEP, 2023:11), which accounted for over 90% of the total electricity produced in the country. This suggested that Ethiopia heavily depended on hydropower. Additionally, with the massive hydropower development over the past two decades, hydropower has become an exportable commodity to Djibouti, Sudan, and Kenya.

Despite such changes, the pace of hydropower development has been a slow process except over the past two decades. In addition, compared to the country's hydropower potential, hydropower development is at its initial stage. Only 4,820 MW is harnessed from 45,000 MW potential. However, the existing literature fails to suggest the megatrends of hydropower development in Ethiopia across periods using a historical and geopolitical lens. Rather, the focus of existing literature is largely limited to the hydropower potential of the country without showing its strategic implications in geopolitical terms (Solomon, 1998; Ashebir and Desta, 2020; Dagmawi *et al.*, 2015; Dessalegn, 2018). Others also studied the hydropower potential and its development in specific river basins (Dereje *et al.*, 2011; Ashebir, 2020), climate change aspect of hydropower development (Block and Kenneth, 2012) and different aspects of specific hydropower projects (Abebe, 2000; Eldardiry and Faisal, 2021; Annys *et al.*, 2020; Annys *et al.*, 2018; Beirne, 2014).

Furthermore, the existing literature has overlooked the implications of the country's hydropower potential to its development and benefits to the region at large specifically from a geopolitical point of view. This study therefore intends to examine how hydropower development is repositioning Ethiopia as a regional anchor state by exploring the strategic importance of its hydropower potential as well as the historical evolution of hydropower development, including the mega trends, changes, and continuities. The research also tried to meet the following objectives:

- ❖ To assess the hydropower potential of Ethiopia by mapping its key features.
- ❖ To analyze the historical evolution of hydropower development in Ethiopia, identifying the major trends, patterns, changes, and continuities.
- ❖ To examine the massive expansion of hydropower development that occurred in the post-1991 period.
- ❖ To show the strategic importance and implications of Ethiopia's hydropower potential and its development.

RESEARCH METHOD

The study employs a qualitative research approach specifically a historical and geopolitical perspective to analyze Ethiopia's emergence as a renewable energy power hub. Data was gathered through key informant interviews with 50 purposively selected individuals from the Ministry of Water and Energy, the Ministry of Foreign Affairs, Ethiopian Electric Power, Ethiopia Electric Utility, the Eastern Nile Technical Regional Office, the Environment Protection Authority, the Ministry of Agriculture, Ministry of Irrigation and Lowland, Ministry of Finance, Project Offices, universities, and research institutes. The names of the key informants were coded to maintain confidentiality and anonymity. Documents such as river basin studies, policies, strategies, programs, project feasibility studies, and environmental and social impact assessments were consulted. Pertinent secondary sources were also used. The data were analyzed using thematic analysis.

Hydropower: Ethiopia's White Oil

Ethiopia has abundant renewable energy sources such as hydro, wind, geothermal, solar, and biomass. The availability of these diverse renewable energy sources is largely attributed to the strategic location of the country, including its diverse and complex geographical, topography, and climatic features. According to different sources, economically feasible hydropower potential ranges from 15, 000 to 30,000 MW (Ethiopian Panel on Climate Change, 2015: 26; Solomon, 1998; KII-35, April 2022). Hence, hydropower is often described as Ethiopia's "blue gold" (Verhoeven, 2011) and "white oil" (Addisu, 2021) that could position it to become a clean energy "powerhouse of Africa" (Ashebir *et al.*, 2020:4).

In addition to its hydropower potential, as presented in Table 1, the country possesses untapped reserves of natural gas (113 billion m^3), solar, wind, geothermal (7,000 MW), coal (300 million tons), oil shale (253 million tons), and agricultural waste. Particularly, the untapped renewable energy potential in the country is a valuable resource that has the potential to enhance its geopolitical position in the global transition towards a renewable-based energy system. However, as depicted in Table 1, the country faces various challenges such as technological, financial, technical, and geopolitical barriers (KII-2, April 2023; KII-35, April 2022), which have hindered the full utilization of these resources.

Table 1: Energy Potential of Ethiopia

Sources		**Unit**	**Exploitable reserve**	**Exploited %**
Hydropower		MW	45,000	< 11
Solar/day		kWh/m^2	Avg. 5.5	< 1
Wind	power	GW	1,350	
	speed	m/s	> 6.5	
Geothermal		MW	7,000	< 1
Wood		Million tones	1,120	50
Agricultural waste		Million tones	15-20	30
Natural gas		Billion m^3	113	0
Coal		Million tons	300	0
Oil shale		Million tons	253	0

Source: Adapted from EEPC, 2014; FDRE, 2019; Gordon, 2018; KI-43, 20 November 2023

Concerning hydropower, Ethiopia has not only abundant hydropower potential but also suitable sites for generating electricity from hydropower sources. The country's diverse and complex geographical, geological, hydrological, and topographical features contribute to the availability of ideal sites for harnessing hydropower. First, in terms of hydrology, Ethiopia has eight river basins such as Abbay, Baro-Akobo, Tekezze, Awash, Omo-Gibe, Genale-Dawa, Mereb, and Wabishebelle. It has also one lake basin (Rift Valley Lakes), and three dry basins (Aysha, Dinakle, and Ogaden) (KII-1, June 2023). These river basins have an estimated surface runoff water of nearly 122 billion cubic meters every year, which is ideal for hydropower generation (Ministry of Water Resources, 2002:2). However, only eight of these river basins have been recognized to have hydropower potential, as shown in Table-2.

Solomon (1998) identified 300 potential hydropower sites with an estimated exploitable potential of 158,700 gigawatt hours per year (GWh/yr) from the various river basin master plans in eight river basins. However, a report by UNIDO and ICSHP (2013:16) suggests that there are over 600 potential sites for hydropower generation in the country, indicating a lack of accurate information about the exact number of suitable locations for this type of energy production in the country. The 1990s national water resources development master plan of the People's Democratic Republic of Ethiopia (PDRE) government, prepared by the Indian Water and Power Consultancy Service, identified 314 hydropower sites across ten river basins, including the Mereb-Gash and Barka-Anseba rivers. Besides, the hydropower potential from small streams, which are relatively small and dispersed, do not require reservoirs (Getahun, 1993 E.C.:286), is also estimated to be 173 hydropower sites (Solomon, 1998).

Second, Ethiopia also has topographical (Meles, 2011) and geological advantages for harnessing water power for development purposes. Though the country's mountainous terrain, steep slopes, and deep gorges may pose challenges for irrigation (Alem-meta *et al.*, 2019: 49), they are highly suitable for various types of hydropower generation such as run-of-river, storage, high head, medium, and low head power plants. Noting the topographical suitability for hydropower, a senior diplomat and energy expert expressed as follows:

> Ethiopian rivers originate in high mountains and flow rapidly downhill towards lower elevations. These rivers flow through steep slopes and gorges, which make them attractive for hydropower generation. Except for the Genale Dawa and

Wabishebele, there are no rivers that flow directly on the flat plains (KII-21, April 2022).

The mountains' headwaters, numerous waterfalls, and the flow of water through steep slopes provide ideal sites for harnessing the natural flow of rivers and streams to generate electricity from falling water without requiring large reservoirs. For instance, the Tis Abay I Hydroelectric Plant which started to operate in 1964 with an installed capacity of 11.4 MW used the naturally created Tis Abbay Fall (Abebe, 2000).

Table 2: Hydropower Potential of Ethiopian River Basins

River Basin	Number of Potential Sites				Hydropower Potential (GWh/year)	Percentage Share of the Total (%)
	Small scale <40 MW	**Medium scale 40-60 MW**	**Large scale <60 MW**	**Total**		
Abbay	74	11	44	129	78,800	48.9
Awash	33	2	--	35	4,500	2.8
Baro-Akobo	17	3	21	41	18,900	11.7
Genale-Dawa	18	4	9	31	9,300	5.8
Omo-Gibe	4	--	16	20	35,000	22.7
Rift Valley Lakes	7	--	1	8	800	0.5
Tekezze-Angereb	11	1	8	20	6,000	4.2
Wabishebelle	9	4	3	16	5,400	3.4
Total	173	25	102*	300	158,700*	100

Source: Solomon, 1998

Furthermore, the rugged terrain and rocks make the country well-suited for storage hydropower because the reservoir has to be built on a suitable reservoir rock type that can store water and has less vulnerability to geological hazards and problems like earthquakes, and leakage (Knowles, 2014:29). The headwaters of the mountains, numerous waterfalls, and the flow of water through steep slopes provide ideal sites for harnessing the natural flow of rivers and streams to generate electricity from falling water without requiring large reservoirs. Particularly the topography, hydrological and geological features of the Abbay and Omo-Gibe rivers provide ideal sites for generating electricity from water power. The Abbay River was appraised as one of the "ideal sites for economic hydropower development" in the national water resources master plan owing to the availability of good reservoirs "on the upper plateau at the head of steep incised ravines" (PDRE, 1989:32). The Ethiopian Electric Light and Power Authority (1997) concluded in its environmental impact assessment report that the Gilgel Gibe Project is "one of the most attractive" hydropower development sites in the country because of its topographical and geological features. Gilgel Gibe III is one of the hydropower projects that take advantage of the country's topography and geography. The dam is located in a deep gorge with sub-vertical walls, making it one of the tallest dams in Africa[1].

However, hydropower should not be taken as a mere resource but rather as one that defines and shapes Ethiopia's geopolitical opportunity and limits. In other words, geopolitics refers to how geographical features _water resources and their developments_ determine the fate of a country (Owens, 2015: 2)

Therefore, water resources and hydropower potential of the country are important elements of its national and regional power matrix. Meaning, natural resources and geographical features such as topography and climate are among the natural determinants of national power (Strategic Studies Institute, 2008: 148). Noting this, a diplomat in the Ministry of Foreign Affairs asserts that Ethiopia has a natural leverage over its water resources, particularly in hydropower, owing to its geographical location (KII-13, June 2021). Besides, Ethiopia has more advantage in producing electricity from hydropower resources than other energy sources at lower prices because of its hydrological, topographical, and geological advantages (KII-38, April 2022).

It also has a comparative advantage at the regional level to produce power from hydropower sources at lower costs (KII-24, May 2022; KII-2, 5 January 2023). The generation cost for 1 kWh from hydro in Ethiopia is $0.09 (ESI-Africa, 2021) on average, whereas the same amount of energy from non-hydropower sources is produced at $0.32 and $0.70 in Djibouti (Guelleh *et al*, 2023:215) and South Sudan (ICED, 2018:2), respectively. Djibouti relies heavily on imported oil for electricity generation (World Bank, 2009:1; Guelleh *et al*, 2023:215). South Sudan relies on fossil fuels, particularly diesel generators, for electricity generations (Africa Development

[1] Gibe III Hydroelectric Power Project Environmental and Social Impact Assessment. Accessed January 2022 from https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and Operations/Gibe%20III_EIA_%20Executive%20Summary%20EBJK%2006-08-08.pdf

Bank Group, 2013:209; U.S. Energy Information Administration, 2022: 8). Half of the installed capacity of electricity generation in Sudan also comes from fossil fuels (U.S. Energy Information Administration, 2022: 8). The dependence of these countries on expensive diesel generators contributes to higher costs and carbon emissions in contrast to Ethiopia. Nevertheless, Ethiopia is more advantageous in attracting investment and entering regional power markets with its low-cost hydropower. In addition to the cost competitiveness, the renewability and reliability of hydro further increases its competitive advantage. As a result, hydropower is a reliable power source to provide electricity on demand (KII-21, April 2022). It is also a clean and green energy with 'no' carbon emissions (KII-38, 21 April 2022; KII-10, 15 July 2023; KII-38, 21 April 2022). Realizing the benefits, Djibouti is now replacing diesel with hydroelectricity imported from Ethiopia, which constitutes 80 to 100% of Djibouti's total electricity (KII-1, July 2023). Ethiopia also exports electricity generated from hydro to Sudan and Kenya serving as a water tower and powerhouse of Northeast Africa. Thus, water and hydropower are strategic resources for the country, linked with national power.

On the other hand, hydropower endowment can also be a geopolitical curse. The transboundary nature of river basins where hydropower resources are found can generate geopolitical tensions with other water users, particularly downstream countries. Except the Awash River, all other river basins flow into neighboring countries. This implies that Ethiopia's geographical location as a "water tower" of the region may be seen as a source of power. However, downstream countries may see Ethiopia as a perceived threat because of the downstream impacts of its water resources development_ hydropower. The Abbay River, which accounts for nearly 49% of the hydro potential of the country (Assefa *et al.*, 2014:111; Casimir, 2005: 7), is a good example of this[2]. Owing to its downstream position, Egypt historically views Ethiopia's water resource plans and

[2] Different studies have reported varying estimates of the hydropower potential share of the Abbay River basin. According to the Ministry of Water, Irrigation and Energy, the hydro potential of Abbay River is estimated to be 13,500 MW, which represents 33.7 percent of the total energy potential of the country. In contrast, the Nile basin capacity building Network's hydropower development research cluster has estimated the hydropower potential of Abbay to be 79,000 GWh/yr, covering 49 percent of the country's total hydropower potential. For more see Casimir, Museruka, Sibilike K. Makhanu, D. Mahauri, D.J. Chambega, C.F. Mhilu, F. Matalo, Ntungumburanye Gerard, Kizza Michael, Keneth Muniina, Zelalem Hailu, David Negula, James L. Ngeleja, I.S.N. Mkilaha, Leonard Kassana, Leonard R. Masanja, and Bela petry (2005). Nile basin capacity building Network hydropower development research cluster: Group 1 Small Scale Hydropower for Rural Development; Ministry of Water, Irrigation and Energy (2013). Water Resources of Ethiopia: The National and International Perspectives [Paper Presentation]. Awareness Creation Program Prepared for Public Relation Officials, August 2013, Addis Ababa, Ethiopia

developments on the Abbay River as "an existential threat", which is neither an actual nor a perceived security threat but rather securitization by imagination. Egypt's fear and anxiety, which emanates from its downstream geographical feature, has been an obstacle to Ethiopia's monetary demands from international financial institutions and donors who are reluctant to provide loans to such contested projects (KII-25 July 2023; KII-27 May 2022). This has rendered Egypt a "veto power" status over external loans for Ethiopia's water projects (KII-13, June 2021). Furthermore, the Abay River along with the Red Sea are the two water systems that make Ethiopia and Egypt adversarial/rival powers of the Northeast Africa geopolitical region (KII-13, June 2021). Hence, the geopolitical adversarial stand of the rivals may continue, Ethiopia being the source of the water and Egypt the furthest riparian. This implies that the strategic location of Ethiopia as a water source and hydropower hub of the region is both an opportunity and a limitation.

Moreover, the country's vulnerability to climate change such as droughts and El Nino could affect the electricity generation capacity of its hydropower plants. For instance, in 2002/3, frequent power disruptions were caused by drought-induced water shortages that affected the power generation capacity of the existing hydropower plants (WB, 2006: xiv). It was estimated that each day of power interruption resulted in a loss of 10-15% of that particular day's Gross Domestic Product (GDP) (WB, 2006: xiv). Similarly, power interruptions in 2009 forced the government to install 60 MW of diesel in Adama, which was observed by the former Ethiopia Electric Utility (EEU) leadership as a costly source of energy (KII-1, July 2023). Thus, the country's hydro dependency and vulnerability to climate change presents a significant challenge that arises from its geographical features. Therefore, it is essential to understand that hydropower development in Ethiopia could have both geopolitical limitations and opportunities. It is a geopolitical opportunity since Ethiopia has geopolitical leverage over hydropower generation, with the potential to become a regional renewable energy power hub. However, certain factors such as the transboundary nature of the rivers and the geopolitical impact of the country's hydropower development may ignite geopolitical tensions with downstream countries, notably Egypt.

Harnessing Water Power for Development

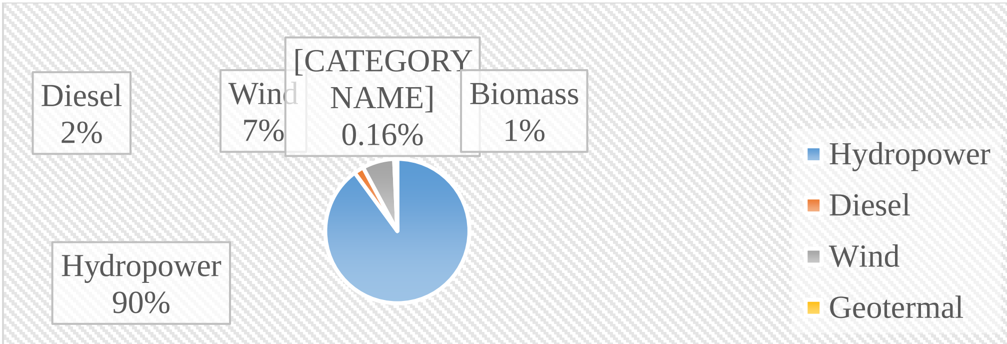
Hydropower is a strategic resource for Ethiopia as it has the potential to boost economic growth and bring about structural transformation. At the same time, hydropower can be an important source of foreign currency through power export to neighboring countries. As stated in the various policy documents of the FDRE government, the generation of electricity from hydropower is a key means to realize the national objectives ranging from poverty reduction to building of climate-resilient green economy, and ultimately becoming a clean energy hub. However, investment in the hydropower sector, which dates back to the early 20th century, was slow until the early 2000s, when it entered a booming period that coincided with the global hydropower re-booming period in developing countries of the global south.

Hence, over the preceding two decades, the country has made significant steps in hydropower generation, transmission infrastructure, and access to electricity. Though the national energy demand is not yet met, the progress in hydropower generation has increased by more than tenfold (KII-1, July 2023; KII-27, May 2022). In 1991, the country installed capacity of 370 MW (EEP, 2017:3), but by 2023 this figure rose to 5,256.5 MW (EEP, 2023:11). 4, 820.2 MW of the installed capacity is from hydropower sources (EEP, 2023:11). Hence, as shown in figure-3, hydropower accounts for over 90 percent of the total energy produced in the country, making Ethiopia hydropower dependent country (Amsalu, 2022:1). The country has also seen significant changes in its transmission lines and substations, with high electric transmission lines increasing from 5,000 km to 20,634 km over the past three decades (KI-53, November 2023). Moreover, more than 192 substations with varying voltage levels ranging from 132kv to 500kv have been constructed (KI-53, November 2023). These developments have led to increased access to electricity, which has risen to 56% (EEP, 2017:3). However, the number is a contested one and varies across different sources. According to the revised National Electrification Program, access to electricity is 44 percent (FDRE, 2019: xiii). In addition to this, a senior energy expert pointed out that per capital electricity consumption in Ethiopia is one of the lowest in the world which is 130kwh, and according to him access to electricity in the country is 51 percent (KII-1, July 2023). Both the key informant and the updated version of the electrification program confirmed that nearly 57 million people do not have access to electricity (FDRE, 2019: xiii; KII-1, July 2023). However, per capita electricity consumption has increased from 100 kWh in 2017 to 130kWh in 2019 (Ashebir and Desta, 2020:5). The country also exports power to Sudan, Djibouti, and Kenya.

These changes are largely owing to changes in the policy and ideological orientations of the post-1991 regime. Among the notable policies, strategies, and programs that encouraged the production of electricity from hydropower included the Climate Resilient Green Economy strategy, Growth and Transformation Plans, National Electrification Program, Power Purchase Agreement, and Digital Ethiopia 2025 strategy. Despite significant progress in hydroelectric power generation, Ethiopia's per capita electricity consumption was the lowest in the world. The challenges included limited access, high costs for construction and new connections, and drought disruptions in hydropower generation.

Institutionally, the two state-dominated enterprises, Ethiopia Electric Power and Ethiopian Electric Utility, are mandated for the power generation and transmission, and power distribution respectively. Other stakeholders included the Ministry of Water and Energy responsible for managing water resources of the country at the national level. With this, the country has two power supply system namely: an interconnected system (ICS) and a Self-contained system (SCS). The ICS is managed by Ethiopia Electric Power. As shown in Table-3, the ICS is mainly supplied by 16 hydropower plants, but also has 4 wind, 1 geothermal and 1 biomass power plants (EEP, 2021:4). There are also 6 diesel power plants. Currently, ICS installed generation capacity amounted to 5,256.5 MW (EEP, 2023:11). Whereas, the SCS is supplied by mini hydropower, thermal plants and isolated diesels.

Figure 1: Power Generation Capacity by Energy



Source: Adapted from EEP, 2021

Moreover, hydropower plants in Ethiopia are classified by their capacity, ranging from large (>30 MW) to pico (≤10 kW) (Meder, 2011:9). Medium power plants have a capacity ranging from 10 to 30 MW whereas small and mini power plants have a capacity ranging from 1 to 10 MW, 501 to 1,000 kW respectively. Micropower plants have a capacity ranging from 11 to 500 kW. However, the classification of hydropower in terms of installed capacity varies from institution to institution. For instance, in the Water Sector Development Program of the Ministry of Water Resources, small-scale hydropower schemes are classified as micro (< 100 kW), mini (100–1,000 kW), and small (1–10MW) schemes (Ministry of Water Resources, 2002: 19). The absence of a nationally defined classification of hydropower according to this size may be explained by the lack of inter-agency coordination study and planning of hydropower development between the stakeholders notably the Ministry of Water and Energy, and Ethiopian Electric Power. According to an informant in the Ministry of Water and Energy, Ethiopia has no clear classification of hydropower in terms of their installed capacity except that in ICS and SCS (KII-27, May 2022). However, another informant disclosed that the classification is done in view of pico, micro, mini, medium, and large scale (KI-43, 20 November 2023).

As clearly shown in the preceding session, the post 2000 period is a hydraulic era that repositioned Ethiopia as an emerging regional renewable energy power hub with a focus on hydropower. However, the development of water power for electrifying Ethiopia and the region has undergone several distinct stages. These can be categorized into two periods: early rapid development (1912-2000) and the hydraulic era (post 2000). Early rapid development can be further divided into three periods: early development (1912-1960), hydropower era (1960-1974) and stagnation (1974-2000). Given this, the following section briefly explores the evolution of hydropower development in Ethiopia and the drastic shift in the pace of hydropower investment since 1991.

Table 3: Interconnected System Installed Capacity by Energy Source Type in MW in 2023

No.	**Power Plant**	**Installed Capacity (MW)**					
		Hydro	**Geothermal**	**Biomass**	**Wind**	**Total**	**Operation Year**
1	Koka	43.2	-		-	43.2	1960
2	Awash II	32	-		-	32	1966
3	Awash III	32	-		-	32	1971
4	Finchaa	134	-		-	134	1973/2003
5	Meleka Wakena	153	-		-	153	1988
6	Tis Aby I	11.4	-		-	11.4	1964
7	Tis Abay II	73	-		-	72	2001
8	Gilgel Gibe I	184	-		-	184	2004
9	Aluto Langano	-	7.5*		-	7.5*	1999
10	Tekeze	300	-		-	300	2009
11	Gilgel Gibe II	420	-		-	420	2010
12	Beles	460	-		-	460	2010
13	Amerti Neshi	97	-		-	97	2011
14	Gilgel Gibe III	1,870	-		-	1870	2015
15	Abasamuel	6.6	-		-	6.6	2016
16	Adama I	-	-		51	51	2012
17	Ashegoda	-	-		120	120	2012
18	Adama II	-	-		153	153	2014
19	Rappie Waste			25		25	2019
20	Genale Dawa	254				254	2020
21	GERD	750				750	2022
22	Ayisha wind				80	80	2022
Total		4,820.20	7.5		404	5,255.70	

Source: Filed Data and EEP: 2018 and 2023

*EEP Fact sheet of 2023; the installed capacity declined to 7.3

Early Rapid Development (1912-2000)

The harnessing of water power for energy generation in Ethiopia began in the early 20th century as part of the country's modernization and industrialization drive under the imperial regime. However, it is important to note that electricity was first introduced in 1898 during the reign of Emperor Menelik II and was supplied by diesel generators, though its service was limited (Ministry of Water, Irrigation and Energy, 2006: 43; Yirgu, 2017:4; Ethiopian Electric Utility, 2022). Electricity generated from hydropower sources was also introduced in 1912 with the construction of a power plant on the Akaka River (Carr, 2017; 23; Yirgu, 2017:4; Getahun, 1993:290; Ministry of Water, Irrigation and Energy, 2006: 43), while others differ in their public knowledge of the plant's history referring to the operation of Aba Samuel Dam with an installed capacity of 6.6 MW in 1941 (EEP, 2018:18).

Emperor Haile Selassie I, following his coronation in 1930, continued in harnessing water power for electrifying and powering Ethiopia, and in 1932, revitalization and redevelopment of the Akaki River were initiated (Carr, 2017; 23). Regrettably, these plans were interrupted by the Italian invasion and subsequent occupation. The Italians expanded the power supply through diesel generators and began the construction of Aba Samuel Hydroelectric Power Plant. During this period, the Italian company Coneil ran the generation, distribution, and sale of electricity having taken over the electric power-related property of the Ethiopian government (Getahun, 1993:290; Yirgu, 2017:4).

The Aba Samuel Hydroelectric Power Plant, commissioned in 1941 with an installed capacity of 6.6 MW, served the post-liberation modernization and industrialization drive of the imperial regime. It supplied electricity to the capital city but was out of service from 1974 to 2016 due to 'reservoir problems and defect" (PDRE, 1989:2), and high silt accumulation from the Akaki River[3]. The plant has since been revitalized through a rehabilitation project funded by the Ethiopian and Chinese governments, with Power China Huadong Engineering Corporation handling the rehabilitation. The revitalized power plant, which was completed in

[3] Clean Rivers Trust. Aba Samuel Reservior. Accessed January 2022 from https://www.cleanriverstrust.co.uk/aba-samuel-reservoir/

2016, has an installed capacity of 6.6 MW[4] (EEP, 2018:18). However, it has to be recalled that a rehabilitation and redevelopment study on the Aba Samuel Power Plant was conducted by UNDP and ENEL in 1983 and 1987, respectively. The finding suggested that redeveloping the power plant "to a total installed peak load capacity of 36 MW' was economically feasible (PDRE, 1989:2). Simultaneously, the study by ENEL showed that only 16-20 MW would be generated from the rehabilitated power plant (PDRE, 1989:2)

In addition to Aba Samuel, another hydropower plant with an installed capacity of 120kW operated in Jimma town (Getahun, 1993:288). The development process covering the period from 1912 to 1952 can be referred to as a slow hydropower development phase.

The second period, which covers the years from 1960 to 1974, was the hydropower era. During this period, major achievements were made specifically the construction of significant hydropower projects such as Koka (43.2 MW), Ourso (0.42 MW), Tis Abbay (7.6 MW), Awash I and II (64), and Fincha (100 MW) (Getahun, 1993:288-289). Additionally, the Ethiopian Light and Electric Authority, currently the Ethiopia Electric Power, was established during this period (World Bank (WB), 1964). Furthermore, a joint study between the US Bureau of Reclamation and the Ministry of Public Works and Communication of Ethiopia led to the identification of potential single and multipurpose hydropower sites on the Abbay River.

Table 4: Hydropower Plants Built from 1941 to 1974

Power Plant	**Installed Capacity in MW**	**River**	**Operation Year**
Aba Samuel	6.6	Akaka River, Awash Basin	1941
Koka	43.2	Awash	1960
Ourso	0.42	---	1953
Tis Abbay	7.68	Abbay	1964
Awash I	32	Awash	1966
Awash III	32	Awash	1971
Fincha	100	Fincha River, Abbay Basin	1973/4
Small Plants	0.43 (*Isolated	----	---

[4] AidData. Chinese Government provides RMB 95 million grant for Aba-Samuel Hydropower Plant Rehabilitation Project [Project ID: 59178]. Accessed January 2022 from https://china.aiddata.org/projects/59178/

	system)

Source: Compiled from World Bank, 1964; EEP, 2021; Getahun, 1993

As in Table 4, the second hydropower plant in the country's hydropower development history was initiated two decades after the operation of Aba Samuel Power Plant. Except Tis Abbay hydroelectric power which supplies electricity to Bahirdar and a textile factory, all hydropower plants feed the main grid (WB, 1964:3; Getahun, 1993). Moreover, there was also mini hydropower that served small towns across the country.

Another salient feature of this hydropower era was the birth of hydraulic bureaucracy and the centralization of planning, generating, and selling of electricity. Ethiopian Light and Electric Authority (ELEA) was the first state-owned hydraulic institution established by the Imperial Charter in 1956 (WB, 1964:1). Other includes the Awash Valley Authority (AVA), Water Resources Department, and National Water Resource Commission[5]. While the AVA was a basin level water management institution responsible for the utilization and management of Awash River, the rest two were national institutions.

ELEA was responsible for the overall power development particularly the production, transmission, distribution, and sale of electricity throughout the country. However, an Italian company granted a concession in 1953 for 44 years supplied electricity to the northern province of Eritrea was by that was (Bureau of Reclamation, 1964a:96-102; WB, 1964:1). While the northern province of Eritrea particularly Asmara and Massawa load centers were mainly supplied by Società Dell' Africa Orientale (SEDAO), isolated towns and villages were provided by other four utilities such as Public Works Department of Eritrea, CONIEL, SAIBO, and SAET (Bureau of Reclamation, 1964a: 102).

However, southern parts of Eritrea were supplied by ELEA which operates both the interconnected system and self-contained system. The Interconnected system mainly serves the fast-growing industrial and commercial centers of the Addis Ababa-Dire Dawa-Harar corridor through a high-voltage transmission line connected to Koka Hydroelectric Power Plant while the isolated system serves small towns such as Jima, Ambo, Dessie, Debre Berahan, Woliso, Yirgalem, Jijiga, Negele, Bahirdar, and factories (Bureau of Reclamation, 1964: 96-100). While

[5] For more see, Yacob Arsano (2007). Ethiopia and the Nile: Dilemmas of National and Regional Hydropolitics. Dissertation, University of Zurich, Zurich

off-peak power was supplied to industries in Addis Ababa, Tis Abba hydroelectric power plant provided power to the Textile Factory in Bahirdar (WB, 1964:5). To address the shortage of skilled manpower, ELEA established its Training Institute in 1960 (ELEA, 1973).

Another breakthrough in the pace of hydropower development of the country during this period was the water resource studies and plans undertaken by the Imperial regime. The 1955 water resource survey and the Ethiopia-US Cooperative Program for the Study of Blue Nile Basin (1958-1964) had far-reaching geopolitical implication to the water resource development of the country. The former undertaken by the imperial regime identified 5,226 MW economically feasible hydropower potential, most of which was located within a 500 km radius of the capital city (WB, 1964:7). In this survey, the annual hydropower production potential from Awash River was estimated to be 1,287 million kWh.

In addition to hydropower potential of Awash, its strategic importance made it a key site for hydropower extraction during the imperial regime. Firstly, Awash is geographically close to the largest load center, the Addis Ababa complex. Most of the suitable hydropower sites in the country are in remote areas and peripheries, but the Awash River is located near the fast-growing industrial and commercial centers of the Addis Ababa-Dire Dawa-Harara corridor and the railway connecting Ethiopia with the Djibouti port. Meeting the energy demands of this political, economic, and commercial corridor was of great strategic importance to the country. Secondly, Awash is an inland river that does not cross the international border of Ethiopia. This means that water resource development would not involve geopolitical tensions. Obtaining finance for projects on the Awash River from international financial institutions may also be easier than for projects planned on transboundary rivers such as Abbay. These factors made Awash River the site for hydropower generation during the imperial regime. While Awash I and II were constructed with funds from the World Bank, the Koka Hydroelectric Power Plant was built using finance obtained from Italy as war reparation (Carr, 2017: 26-27).

Another study with significant geopolitical implications for Ethiopia's hydropower development was the Ethiopia-US Cooperative Program for the Study of the Blue Nile Basin (1958-1964). The program aimed to investigate land and water resources of the Abbay River basin, establish an appropriate water resources management organization capable of continuing the investigation in other river basins, and provide training to Ethiopian personnel in administering this organization (Bureau of Reclamation, 1964a: I; 1961d: 1). The study began in early 1958 and was completed in 1964. The final report, titled "The Blue Nile Land and Water Resources in Ethiopia," consisted of one volume and six appendices specifically plan and estimates, hydrology, geology, land classification, power, agriculture, and economics.

The study identified 33 potential hydropower and irrigation sites, particularly their productive potential and costs, and four mega hydropower projects: Karadobi (5,835 million kWh per year), Mendaia (7,800 million kWh per year), Mabil (5,314 million kWh per year), and Border (6,200 million kWh per year). Although Fincha Hydroelectric Power was reported to have been completed, the GERD was identified as being currently under-construction. The report also listed several hydropower and irrigation sites that were considered less feasible due to inaccessibility, remoteness from the grid, and less desirable dam and reservoir sites (US Bureau of Reclamation, 1964c: 253). The electricity generation capacity was estimated for 10 promising hydropower sites. Furthermore, the study concluded that Abbay River Basin is less feasible for irrigation, and its potential is largely restricted to hydropower. The construction of the identified hydropower projects, according to the study report, would benefit downstream countries by regulating the water flow and retaining sediments.

Table 5: Identified Hydropower and Irrigation Projects on Abbay by Bureau of Reclamation, 1964

Identified Project	**Project Purpose**	**Reservoir**		**Irrigable Area (ha)**	**Installed Capacity (kW)**
		River	**Installed Capacity (Million cubic meter)**		
Megech Gravity	Irrigation	Megech	225.3	6,940	
Ribb	Irrigation	Ribb	312.6	15,270	
Gumara	Irrigation	Gumara	236.7	12,920	
West Megech Pump	Irrigation	Lake Tana	12,987.0	7,080	
East Megech Pump	Irrigation	Lake Tana	12,987.0	5,890	
Northern Tana Pump	Irrigation	Lake Tana	12,987.0	5,000	

Identified Project	Project Purpose	Reservoir		Irrigable Area (ha)	Installed Capacity (kW)
		River	Installed Capacity (Million cubic meter)		
Upper Beles	Multipurpose	Lake Tana	12,987.0	63,200	200,000
Middle Beles	Hydropower	Beles	3,974.0	---	168 000
Upper Birr	Irrigation	Birr	537.4	24,350	
Debohila	Irrigation	Debohila	50.1	4,200	
Lower Birr	Irrigation	Birr	Run of River	6,600	
Giamma	Hydropower	Giamma	3,169.0		60,000
Muger	Hydropower	Muger	300.7		26,000
Upper Guder	Irrigation	Bello	70.6	5,100	
Lower Guder	Hydropower	Guder	2,557.0		50,000
Fincha	Multipurpose	Fincha	464.0	15,000	80,000
Amarti-Neshe	Multipurpose	Amarti and Neshe	847.6	8,490	80,000
Arjo Diddessa	Multipurpose	Diddessa	2,130.0	16,800	30,000
Dabana	Multipurpose	Dabana	1,617.0	6,100	85,000
Angar	Multipurpose	Angar	3,572.0	30,200	185,000
Lower Diddessa	Hydropower	Diddessa	4,862.0		320,000
Dabus	Irrigation	Dabus	Direct Diversion	15,000	
Dabus	Power	Dabus	---	---	7,500
Dindir	Multipurpose	Dindir	3,690.0	58,300	40,0000
Galegu	Irrigation	Galegu	798.8	11,600	
Rahad	Irrigation	Rahad	1,902.0	53,100	
Karadobi	Hydropower	Abbay	32,500.0		1,350,000
Mabil	Hydropower	Abbay	13,600.0		1,200,000
Mendaia	Hydropower	Abbay	15,930.0		1,620,000
Border	Hydropower	Abbay	11,074.0		1,400,000
Addi, Ababa-Asab Trans	Hydropower	---	---		
Jiga Spring Pilot	Irrigation	Turkar Spring	Direct Diversion	224	
German Gilgel Abbay	Multipurpose	Jema, Koga, Gilgel Abbay	1,017.0	62,390	63,665
Sum			118,427.8	433,754	6,965,165

Source: United States Department of the Interior Bureau of Reclamation, 1964a

However, the joint study program on the Abbay River by Ethiopia and the US was not without criticism. Critics argue that the cooperative program for the study of the Blue Nile Basin was largely motivated by Cold War geopolitics rather than a pragmatic need. Firstly, the lack of implementation was associated with the US's reluctance to provide finance for the identified projects. Waterbury (2002:69) argued that the study was not "a blueprint for Blue Nile development" but rather it clearly implied Cold War geopolitics.

Secondly, some claim that the study was not driven by demand but it was a geopolitical response by Addis Ababa and Washington to Cairo's High Aswan Dam and the Cairo-Moscow alliance, respectively. A senior water expert questioned the very intention of the study program and asserted that the rationale behind the 1958-64 Abbay River Basin study needs to be questioned whether it was driven by development needs to meet national energy demand or a response to Cold War geopolitics:

> the study was initiated suddenly, and no preparations were made. If it was driven by development needs, we would have seen some implementations. However, there was no finance available for these projects, and even the regime faced problems obtaining finance for Fincha. During that time, energy-demanding sectors such as urbanization and industrialization were in their infancy stages, and the majority of the population was agrarian, can rely on annual rainfall which was sufficient (KII-28, May 2022).

The absence of high energy demand at the national level seems more convincing which is also further supported by the personal experience of a senior energy expert who held top leadership positions in the energy sector:

> during the 1970s, there was surplus electricity generated from different sources, but the community was unable to use this surplus energy because most of the population was agrarian, and there was no urbanization. The EEPA had to find a solution and applied various incentive packages to encourage the community to use electricity. One of the incentive packages was a low tariff for users who consumed more energy. The logic behind this was that the more electricity you use, the less you pay per unit, while those who used less electricity paid a higher tariff. Secondly, the EEPA began producing and selling electric pans (KII-1, July 2023).

Another view by an experienced energy specialist adds weight to this issue. According to him, during the pre-1991 era, power usage remained relatively low. He explained this by comparing the past energy surplus with the present energy crisis: “elderly people who were customers of EEPA in the 1970s and 1980s told us that “in those days, we didn't experience power outages [ድሮ መብራት አይጠፋም ነበር]. However, there have been times since 1991 when the country faced energy shortages and even crises” (KII-9, May 2022). Another key informant also noted that the study was unrealistic because it was conducted in the absence of geopolitical conditions necessary to proceed with the construction of hydropower dams (KII-31, April 2022). Furthermore, there was a lack of finance, transmission and substation infrastructure, and ultimately, no users (KII-31, April 2022).

In order to fully understand the potential geopolitical motivations behind the joint study program on the Abbay River by Ethiopia and the US, it was necessary to examine the geopolitical landscape of Northeast Africa during the Cold War and post-Cold War periods. Major geopolitical events during the 1950 and 1960 are this time contributed to a realignment of interests between Ethiopia and the US. One such event was the antagonism between Gamal Abdel Nasser and the US was attributed to the withdrawal of US from financing the High Aswan Dam. In response, Nasser nationalized the Suez Canal and constructed the dam with Soviet funds and technical support (Zewude, 2006: 9-18; Teferi, 2004:135-136). This created a crisis in the West (Erlich, 2002:132), and geopolitical fear in the US owing to the potential spread of communism following the Egypt-USSR alliance. On the other hand, Ethiopia was irritated by Egypt's monopolization of the Nile water through bilateral agreements which excluded upstream countries like Ethiopia.

The Ethiopian imperial regime's immediate countermeasure to the High Aswan Dam was to construct water controlling infrastructure on Lake Tana, built by Italian and French companies (Zewude, 2006:12). Playing Sudan against Egypt was also another countermeasure that was considered (Erlich, 2002:133). However, in opposition to Egypt's alliance with the USSR and the unfeasibility of constructing a dam on Lake Tana, the imperial regime invited the US, to undertake a joint preliminary study on the Abbay River (Zewude, 2006:12-23). This common geopolitical interest led Ethiopia and the US to conduct a joint study program on the Abbay River.

The involvement of the US in the study program was a tactical alliance, which was contrary to its current opposition to the construction of the GERD. It was recalled that the US in the 1950s and 1960s had expressed its concerns about the negative impacts of Egypt's unilateral water resources development on Ethiopia and other riparian countries (US National Security Council, 1960). The US aimed to systematically alienate Egypt from the USSR and send a clear message that if Egypt threatened US interests, then the US would help Ethiopia construct the identified projects on the Abbay River (KII-11, November 2021). In 1956 the U.S also formally assured Ethiopia that "no action in derogation of Ethiopia's legitimate rights [to the Nile water] should be taken without Ethiopia's consent" (US National Security Council, 1960). However, the US's policy shifted after the Camp David Accords, resulting in a shift from protecting Ethiopia's water rights to shielding Egypt's water security.

In contrast to this, for Ethiopia, the joint study is a tactical-cum-strategic move. It is tactical in the sense that it is a countermeasure to the unilateral move of Egypt. It is strategic because the study is a continuation of the country's hydropower development, and the construction of hydraulic infrastructure in accordance with the study could reposition the State as the powerhouse of the region in the long run.

Hence, the joint study program on the Abbay River by Ethiopia and the US had significant geopolitical implications. Firstly, the program played a crucial role in increasing the structural and expert power of Ethiopia in terms of water resources development and management. Structurally, the study program led to the establishment of the Water Resources Department in 1959 (US Bureau of Reclamation, 1964a: II). In terms of expert power, 71 Ethiopians participated in the study program, gaining the skills and experience needed to manage, study and utilize the country's water resources (Water Resource Department, 1952/1960). This served as the foundation for the country's journey towards having a well-equipped hydraulic human power. Secondly, the study served as a baseline for the river basin master plan and hydropower master plan undertaken by the Ministry of Water and Energy and Ethiopia Electric Power, respectively. Lastly, as knowledge is a crucial element of power, the study program could be used as a reference in water resources study and related negotiations. This knowledge can be leveraged in future negotiations to ensure that Ethiopia's interests are well-represented and protected.

Besides, Ethiopia's interest to electrifyAfrica through continental power grid was also entertained during the imperial regime. The country hosted the first African Electric Power Conference under the auspices of the Economic commission for Africa in Addis Ababa, from October 21-31, 1963[6]. The conference was attended by delegates from 21 African countries, 14 observers from non-Africa countries, and 7 representatives from international financial and energy institutions. In this meeting, Ethiopia emphasized the importance of the untapped energy potential of Africa including hydro for realizing African unity through establishing African electric power grid.

In sum, the last two decades of the imperial regime witnessed high progress in the energy sector in general, and hydropower in particular. Globally, the period from 1930s to the 1970s was also a 'high dam era' particularly in the North America, and Europe[7]. As it was the case in the global north, the drivers for hydropower development in Ethiopia during the imperial regime was also largely linked to modernization and industrialization drive of the State. The taming of rivers for generating electricity was also limited to rivers proximate to the center, Addis Ababa, and the major commercial center along the Djibouti-Addis Ababa Railway, the Addis Ababa-Dire Dawa-Harar corridor. This shows that the generation, transmission, and distribution of electricity were largely determined by the energy demand from the growing industrial and commercial centers. The regime was also successful in obtaining technical and financial support from international financial institutions by instrumenting the geopolitical position of the State, and at times by playing one power against the other (KII-21, April 2022).

The final sub-development phase of the early hydropower development stage (1912-2000) was the stagnation period (1974-2000), which coincided with the global decline and stagnation of hydropower (1970-2000). During this period, only one hydropower project, Melka Wakena with an installed capacity of 153 MW, was operational in 1988. The construction of the Gibe I Hydroelectric Project was initiated by North Korea during this period (KII-1, June 2023). On top of the slowing down of hydropower development, some power plants, such as Aba Samuel, were out of service. Regrettably, Melka Wakena, constructed on the Wabishebelle River, was unable

[6] Minute of report of the African Electric Meeting, E/CN.14/INR/32, 27 November 1963

[7] Lee, Gabriel (n.d). The Big Dam Era, Energy History, Yale University. Accessed on February 2022 from https://energyhistory.yale.edu/units/big-dam-era

to produce its full installed capacity because of reduced inflow of water to the reservoir and water loss owing to evaporation. Simulation studies revealed that Melka Wakena generates only 12.21% of its installed capacity (Bosona and Gebresenbet, 2010:87; Brook and Teshale, 2022: 3). Except for the year 2022, overflow had never been recorded in the history of this dam (KII-28, May 2022).

The factors that contributed to the stagnation of hydropower development during this period were financial constraints, geopolitical factors, political instability, policy and institutional barriers. First, internally the energy sector faced problems such as unchanged electricity tariff rate, increased operation costs, and absence of manpower and management organized under the principle of meritocracy (Getahun, 1993:313). A senior dam operation expert also noted that one of the problems in the energy sector was that there was "no professional autonomy and freedom, projects were led by cadres" (KII-2, January 2023). These problems hindered the capability of ELEA to construct new hydraulic infrastructure by covering its costs, even to maintain and rehabilitate existing ones (Getahun, 1993:313). Hydropower plants that were out of service like Aba Samuel had to wait for the hydraulic era. Second, the government policy prohibited private producers and suppliers. This had made ELEA the only electric utility.

Third, factors such as political instability, severe drought, civil war, and external war with Somalia forced the regime to shift resources to war zones and drought response measures. The political instability, civil war, and the external war with Somalia had also a direct link with the water resources development plan of Ethiopia. Owing to the far-reaching geopolitical implication of the Ethio-US Abbay River study and the overall water resources development plan of Ethiopia to Northeast Africa, Egypt pursued a policy of destabilization aimed at weakening Ethiopia, and creating political and security crisis so as to impede water resources development. To secure its monopolization of the Nile water, Egypt supported subversive activities against the Ethiopian government, indirectly through supporting insurgencies in Northern Ethiopia, EPLF and TPLF, and Somalia's irredentist movement in the East. The study by Teferi (2018) revealed that during the Ethio-Somalia war, Egypt provided military support for the invading forces of Somalia, which was nearly 30 million dollars (p. 281). Quoted in Teferi (2018: 278), the former president of the PDRE government also disclosed the strategy Egypt used against Ethiopia to prevent

Ethiopian leaders and future generations from constructing hydraulic infrastructure on the Abbay River by instigating proxy war. This shows that political instability in Ethiopia best serves the interest of Egypt because resources will be spent on war rather than water-intensive hydraulic developments. Thus, because of the 17 years of political instability, the Derge regime's main focus was on 'extinguishing fires' rather than promoting development (KII-11, November 2021). The regime's motto was also not centered on 'development' but rather 'all to the front' [ሁሉም ወደ ግንባር]" (KII-21, April 2022).

Fourth, the lack of external financial support for hydropower projects due to the shift in the global hydropower financing landscape was also another factor that affected the pace of hydropower development during the Derge regime. Globally, in the 1980s and 1990s, international financial institutions such as the World Bank declined to provide funds to large-scale hydropower projects over the adverse socio-environmental impacts of these infrastructures. For instance, in the 1990s, the World Bank withdrew or reduced its funding for hydropower projects around the world (World Bank, 1989:6; WCD, 2000: 19). International financial institutions lack of interest on large-scale water resource development had thus affected the hydropower development of the Derge regime.

Despite these constraints, the PDRE regime through Ethiopia’s Valleys Development Studies Authority undertook a ‘preliminary country-wide water resources development master plan’. The study was conducted by the Indian Water and Power Consultancy Service (WAPCOS) from April 1988 to June 1990. The study aimed to assess the water resources of the country, including their availability, location, and characteristics (PDRE, 1990a). The study was directed to determine the present and future water requirements of the country and identify its hydropower potential. Moreover, the study aimed to propose a framework for the fair distribution of water resources to all areas and suggested measures for preserving the environment. Furthermore, the study targeted to identifying projects, prioritizing them, and establishing an implementation schedule within a given time frame.

Table 6: Hydropower Projects Identified Under the PDRE Master Plan

Rivers	Number of sites	Technical hydropower potential Gwh/yr
Abbay	132	78,820
Awash	43	4470
Baro-Akobo	39	18,880
Genale-Dawa	31	9270
Omo-Gibe	23	36,560
Rift Valley Lakes	6	800
Tekezze	15	5980
Wabishebelle	18	5440
Mereb-Gash	10	760
Barka-Anseba	6	80

Source: PDRE, 1990a

The final report of the study comprises 11 volumes, along with 19 annexes that cover various topics such as topography, hydrology, agronomy, hydrogeology, geology, environment, seismology, and irrigation and hydropower project sites. As shown in Table 6, the study identified a total of 314 hydropower projects, 60 major irrigation and multipurpose projects, and 26 medium projects. These projects were ranked based on their financial feasibility and development priorities.

According to the master plan, the gross hydropower potential of the country was estimated to be 212,810 Gwh/yr, whereas the technical potential amounted to 145,610 Gwh/yr (PDRE, 1990a). The identified hydropower projects had been prioritized based on their development needs to meet the energy demand for the next 50 years. Furthermore, the government had a plan to construct 'one dam every five years' (KII-2, January 2023). With these two initiatives as a breakthrough, some argue that this period was characterized by a strong interest in constructing hydraulic infrastructure on a massive scale (KII-2, January 2023).

The Hydraulic Era (post-2000)

Hydropower development in Ethiopia had been booming since the post-2000 period, marking the hydraulic decades that spanned from 2000 to the present. This era was dubbed the 'big dam era’ owing to the boom in hydroelectric power infrastructures, installed and generation capacities, transmission lines, and substations. Furthermore, it was a period in which the water and energy sector had witnessed structural changes which could be explained by the promulgation of the first water management policy, the establishment of the first Ministry of Water Resources, the splitting of the former EELA into Ethiopia Electric Power and Ethiopia Electric Utility, and establishment of water and energy-related regulatory authorities and agencies, and the introduction of various policies, strategies and programs that incentivized and encouraged water resources development including hydropower. Furthermore, it was a period that witnessed a strategic shift in the consideration of hydropower as a means to multiple ends simultaneously.

This 'hydraulic decade' also occurred concurrently with the global restoration and booming period of hydropower development in the global south such as China, Brazil, India, Laos, and Turkey. Ethiopia was among the new big dam builders of the post-2000. After a period of decline and stagnation in the 1970s and 1980s, large-scale hydropower projects returned to the development agenda of developing countries and funding agencies. Suspended projects owing to alleged environmental and social concerns like Arun-III were constructed (Saklani, 2021). In Ethiopia too, delayed and planned projects like Gibe I, and Border Dam, and Amerti Nesh respectively had become a reality. Rivers in the global south such as Amazon, Mekong, Abbay, Omo-Gibe, and Congo had also become the new hydropower sites for the new dam builders and financiers.

The major factors that drove hydropower booming after its stagnation in the 1980s were the emergence of new dam builders and financiers like China, and the return of traditional financial institutions to finance hydropower projects due to its strategic importance to attain global environmental and developmental goals like MDGs, SDGs, net-zero emission, and the just transition to low-carbon and climate-resilient economy. Particularly, the rise of China as an infrastructure financer was 'an emblematic shift' in the hydropower investment landscape of Ethiopia (Casco, 2009:260). Ethiopia got an alternative source of finance other than the traditional Western donors who were reluctant to finance upstream countries' projects without the consent of downstream countries (Institute of Development Studies, 2013:2; Casco, 2009:260). Furthermore, China involved in Ethiopia's hydropower sector when international financial institutions like the World Bank drastically reduced their investment in hydropower projects because of the alleged negative socio-ecological impacts of the dams (Wang, 2012). For instance, by 1999, the World Bank had not approved any loans for hydropower worldwide.

It is in this global context that China became "a strategic technical and financial partner for the Ethiopian power sector" (Alao *et al.*, 2019:14). Without Chinese involvement, some of the hydropower projects in Ethiopia having both national and regional significance could not have been realized. The Gibe III hydropower project was a good example. When international and regional financial institutions like the World Bank, Africa Development Bank, and European Investment Bank retreated from financing Gibe III due to their concern about the negative social and environmental impacts of the dam (Killoh *et al.*, 2020:415), Chinese financial institutions provided the funds for the construction of the project.

Apart from changes at global level, new geopolitical developments in the Nile and East Africa region served as regional incentives that favored hydropower development. This required the establishment of NBI, EAPP, and the signing of the Nile River Basin Cooperative Framework Agreement. Nationally, because of the relative political stability and double-digit economic growth since 2000, the country was in a better position than in the distant past to run a water resources development. GERD, for example, is currently being constructed by mobilizing domestic resources, government bonds and private donations. Moreover, since the early 2000s, the regime has introduced new policy and institutional frameworks that further accelerated development in the hydropower sector. The major policy measures included: the First National Energy Policy, Water Resources Management Policy, the 2001 water sector policy and strategy, Environmental Policy, the Agriculture Development-Led Industrialization Strategy (ADLI), the Sustainable Development and Poverty Reduction Program (SDPRP) from 2002/03-2004/05, the Plan for Accelerated and Sustained Development to End Poverty (PASDEP) from 2005/06-2009/10, GTP I and II, the Ten-year Development Plan (2021-2030), the Climate-Resilient Green Economy strategy, the Industry Development Strategy, City and Industry Development Strategy, the Ethiopian Power System Expansion Master Plan (EPSEMP), River Basin Integrated Resources Development Master Plans, and the National Electrification Program. All these policy reforms created a conducive environment for massive public investment in the hydropower sector.

With these changes at three levels, development in the hydropower sector boomed substantially. The installed capacity of the country generated from hydropower sources increased from 370 MW in 1991 to 5,256.5 MW in 2023 (EEP, 2023:11). Besides, massive hydraulic infrastructure construction was undertaken: Gilgel Gibe I (184 MW), Gilgel Gibe II (420 MW), Gilge Gibe III (1,830 MW), Genale Dawa (254 MW), Tekeze (300 MW), Amarti Nesh (95 MW), Beles (460 MW), and the GERD (6000 MW), and Koyisha (2160 MW). Rehabilitation of existing hydropower plants (the Fincha, Tis Abbay I, and Aba Samuel hydropower projects) was also completed. .

Table 7: Hydropower Plants Built During the Big Dam Era (2000 to Present)

Power Plant	Installed Capacity in MW	River	Operation Year	Notes
Finchaa	134	Finchaa, Abbay River	1973 (Rehabilitated in 2003)	
Tis Abay II	73	Lake Tana/Abbay	2001	
Gilgel Gibe I	184	Gibe	2004	
Tekeze	300	Tekeze	2009	Cascaded with Gibe II
Gilgel Gibe II	420	Gibe-Omo	2010	Cascaded with Gibe I
Beles	460	Lake Tana	2010	
Amerti Neshi	95	Neshi	2011	
Gilgel Gibe III	1,870	Gibe-Omo	2015	Cascaded with Gibe IV (Koyisha)
Aba Samuel	6.6	Akaki	1941/ (Rehabilitated in 2016)	
Genale Dawa 3	254	Genale Dawa	2020	Cascaded with Dawa Iv
Sor	5			2014
GERD		Abbay		Under construction
Koyisha				Under

				construction, Cascaded with Gibe III

Source: Adapted from EEP, 2021

The Amarti Nesh and the GERD projects were among the 33 identified projects by the Bureau of Reclamation study as part of the Ethiopia-US study program for the Abbay River. Gilgel Gibe I initiated during the Derge regime was completed during the EPRDF reign. In addition to generation, substantial progress was made in the construction of transmission lines and substations, and linking of electric power to the national grid which varied between 132 and 500 kv high voltage transmission lines covering 20,634 km (KI-53, November 2023). Moreover, more than 192 substations with varying voltages had been constructed (KI-53, November 2023).

Moreover, the incumbent government was running hydropower projects that would meet the energy generation goal as set in the ten-year development plan. In this plan, power generation capacity was planned to increase from 4,478 MW to 19,900 MW, transmission line length from 18,400 to 29,900 km, and energy export volume from 2,803 to 7,184 GWH (Planning and Development Commission, 2021:55). These goals were set to meet the growing energy demand both at national and regional levels. Furthermore, in the post-2000 hydraulic era hydropower development was perceived as a *sin quo non* for attaining the policy objectives by 2025 in terms of attaining a regional energy hub, poverty reduction, climate-resilient green economy, and regional integration.

Table 8: Generation Planning

Name of the Project	Installed Capacity (MW)	Notes
Beko Abo	935	
Chemoga Yeda I & II*	280	Under consideration for construction by Public-Private Partnership
Genji	214	
Upper Mendaya	1700	
Genale 6	246	Under review, in the process of bidding to be built by Public-Private Partnership
Karadobi	1600	

Name of the Project	Installed Capacity (MW)	Notes
Upper Dabus	326	
Geba 1 + Geba 2	372	
Sor 2	5	
Gibe IV + V	2132	Gibe IV is under construction
Birbir R	467	
Baro 1 + Baro 2	645	
Genale 5	100	Prequalification stage for PPP
Werabesa + Halele	436	Under review, in the process of bidding to be built by Public-Private Partnership
Tams**	1700	
Gojeb	150	
Lower Didessa	550	
Tekeze II	450	
Aleltu East	189	
Aleltu West	265	
Lower Dabus	250	
Wabi Shebele	88	

Source: Compiled by the Author from the EAEPP and EEP master plans, and FDRE, Public Private Partnership, Directorate General. 2021

*In 2009, a construction agreement was signed with SinoHydro Company. However, in 2014, the agreement was canceled owing to opposition from the International Water Rights Institute on the claim that the project did not meet pre-qualification requirements. Despite this setback, the project was listed as a candidate project for GTP II to be constructed through a public-private partnership.

**Tams will be considered after completing Baro 1 and 2. The installed capacity in the EEP master plan was 1700 whereas in the EAPP, it was 1700 MW

CONCLUSION

Through the analysis of various trends, patterns, changes, and continuities, the study aimed to understand how Ethiopia was emerging as a regional renewable energy power hub focusing on hydropower. The primary reason was associated with three key factors: vast hydropower potential, the consideration of hydropower development as a priority across the regimes, and hydropower booming since 2000. The first factor that contributed to Ethiopia's potential to become a regional renewable energy power hub was its geographical advantage. The country's hydrological, geological, and topographical features made it suitable for hydropower development. This would render Ethiopia the potential to reposition itself as a powerhouse and battery of the Horn of Africa, highlighting the country's strategic importance in the region's energy landscape.

Second, the country had a good historical precedent for harnessing water power. This was indicated in the basin-wide studies, master plans, and the hydropower development ambition of the three successive regimes. These envisaged the country's hydropower potential as a means to attain national and regional goals, build a hydraulic state, and make the country a regional renewable energy power hub.

Since the turn of the millennium, Ethiopia has experienced rapid growth in its hydropower industry. Installed capacity increased nearly tenfold in just two decades, reaching 5,256.5 MW in 2023. As a result, hydropower contributes over 90% of the country's overall electricity production. The change in the hydropower sector has also enabled the country to export power to Kenya, Djibouti, and Sudan.

Furthermore, the pace of hydropower development has also four distinct patterns. The first pattern is the entanglement of domestic and international politics which has been a significant factor in the boom and stagnation of hydropower development. When the domestic and international environment is conducive, hydropower tends to boom, but it declines and stagnates when international geopolitical developments become barriers. This was evident during the period of massive hydraulic infrastructure construction from 1960 to 1974, which coincided with the global hydraulic era. The stagnation of hydropower development between 1974 and 2000 corresponded to the global hydropower decline period of the 1970s and 1980s because of global anti-dam movements. The boom in hydropower since 2000 has also coincided with the global restoration and re-booming period of hydropower in the global south such as China, Brazil, and India.

The second pattern is the strong correlation between political stability and hydropower booming. The relative political stability of the post-liberation period of the Imperial regime and the post-2000 EPRDF reign witnessed the construction of massive hydraulic infrastructure. Conversely, the war period of the military regime experienced the decline and stagnation of hydropower development. Between 1974 and 2000, only the Melka Wakena Hydropower project was operational. However, Koka, Tis Abbay, Awash I and III, and Fincha were constructed and operated between 1960 and 1974. Since 2000, several hydropower projects, such as Tekeze, Gilgel Gibe I, Gibe II, Gibe III, Beles, Amerti Neshi, and Genale Dawa 3 have been completed. Still, other projects such as the GERD and Koyisha are under construction and many others are in the pipeline.

The third pattern is the hydropower sector's role as an exemplary showcase of the regime's foreign policy orientation, power balance, and alliance. Each regime tried to gain technical and financial support from its international allies. For instance, the US-Ethiopia joint program for the study of the Abbay River Basin was a result of the allied interests of the US and Ethiopia during the Cold War. North Korea and the USSR were also involved in the construction of Gilgel Gibe Hydropower Projects and basin-wide studies of the Derge regime, respectively. China has been a major player in the post-2000 hydropower development of the EPRDF era as a dam builder and financier. Furthermore, across the three regimes, the country's hydropower resources were considered strategic in achieving domestic and regional goals, including regional integration. While power trade is a recent phenomenon, the intention of electricity trade has been an element of continuity. The fourth pattern is that hydropower development was state-led although some water resources development studies were in response to rival powers, notably Egypt.

Some of the changes witnessed in the post-2000 hydraulic era included the establishment of the first Ministry of Water Resources and the promulgation of water and energy policies that transformed the water and energy sector structurally. Second, the introduction of policies, strategies, and programs that incentivized and encouraged the generation of electricity from hydropower sources further contributed to the booming of hydropower. Third, hydropower development shifted from rivers close to the center to the peripheries. Fourth, new dam builders and financial institutions have been involved in the hydropower industry development. Finally, the regime's attempt to mainstream and integrate global development and environmental agendas and goals helped legitimize hydropower development as an instrument not only to achieve domestic ends but also global goals.

Barriers to hydropower development across regimes also included the transboundary nature of rivers, lack of finance, geopolitics, political instability, lack of technology and manpower, project delays, lack of private investors, and weak water institutions. Political instability and lack of finance were major constraints during the Derge regime, while the geopolitical context of the rivers was a major factor constraining hydropower development on the Abbay across all regimes.

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Evaluation of meteorological drought and its impact on cereal yield over Afar region, northeast Ethiopia

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Abstract

Drought is a natural disaster resulting from an extended period of insufficient precipitation, leading to an inability to meet the needs of humans, livestock, and the environment. In Ethiopia, frequent and severe droughts increasingly affect the socio-economic and environmental sectors. This study evaluates the current and future projected meteorological drought and its impact on major cereal crops yield over the Afar region in northeast Ethiopia. We used surface stations, satellite climate estimates, downscaled atmospheric reanalysis, and regional climate model datasets. We evaluated the occurrence of drought using the Standardized Precipitation Index (SPI) and Standardized Precipitation and Evapotranspiration Index (SPEI) calculated at 3-month and 12-month time scales. The drought vs. regional cereal yield is correlated to explain yield variability in the region. Results showed that more intense droughts were analyzed in 1984, 1985, 2002, 2008, 2009, 2010, 2015, and 2016. Among these years, 1984, 2002, 2008, 2009, and 2015 were the driest years across all locations in the study area. The regression of SPI and SPEI with yield showed that the indices significantly explained (r^2 = 0.56 for SPI and 0.18 for SPEI) the observed yield variation. Spatially, more intense drought prevails over the northern, northwestern, and southwestern parts of Afar, where these parts are more prone to severe drought. The projected drought pattern showed increases in the intensity and frequency of drought in the middle and end of the century. The findings of this study are helpful for stakeholders working on drought mitigation in the region.

Keywords: climate change, crop yield, drought projection, meteorological drought.

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1 INTRODUCTION

Drought is a natural hazard and recurrent climatic event caused by a deficiency of precipitation with prolonged periods of high temperature (WMO, 2006) Drought occurs in nearly all parts of the world and all economic systems with varying frequency and severity (Wilhite & Glantz, 1985). Its magnitude, duration, and frequency govern the impact of drought. Drought magnitude refers to the amount of rainfall deficit at a particular place and specific time, whereas duration refers to the length of time a drought event stays (Saravi et al., 2009). Drought intensity is the ratio of drought magnitude to duration, which indicates the level of severity or degree of deficit. Meanwhile, drought frequency is the number of drought events in a given time and indicates how frequent drought is in a specific area (Mohammed et al., 2018).

The ongoing climate change has a significant impact on drought. Drought's intensity and duration increase when temperature rises because a higher temperature causes more evaporation and surface drying. For example, the earth's surface air temperature over global land area has increased by about 1.7% since 1970 (Dai, 2011). Studies showed that the global arid zone is very dry, increasing from 10–15% in the early 1970s to 30% in 2002 (Dai, 2011; Feng & Zhang, 2015). Drought has increased worldwide over the 20th century (Aiguo et al., 2004; Trenberth et al., 2014). Studies revealed that drought had become more frequent and intense since 1970, affecting African countries more, with most of this drought caused recently. For example, the frequency and intensity of numerous extreme, multi-year droughts increased every century, with the longest and most intense drought recently occurring in the Sahel and equatorial countries of East Africa (Masih et al., 2014). For instance, estimates of the impact of drought indicate that between 1900 and 2013, about 291 droughts were recorded in Africa, causing enormous losses to humanity, killing almost a million people, and causing an economic loss of over 3,000 million dollars (Masih et al., 2014). Many scholars have investigated future drought changes using projected climate datasets (Teshome & Zhang, 2019, Haile et al., 2020). Haile et al. (2020) indicated a decreasing rainfall trend for the June-September primary rainy season and increased variability for the February to May rainy season over Ethiopia. The projected rainfall extremes of very wet days and the number of heavy rainfall days showed a decreasing trend (Teshome & Zhang, 2019). Both daily maximum and minimum temperatures showed a significantly increasing trend. Accordingly, in Eastern Africa, drought conditions are likely to increase by 16%, 36%, and 54% by the end of the century under low, medium, and business-as-usual emission scenarios, respectively (Haile et al., 2020).

In Ethiopia, more severe and frequent droughts are increasingly affecting the socio-economic sector, particularly the agricultural sector. Agriculture makes up the majority of the country's economy, as more than 95% of the crop production is based on rain-fed agriculture (Minda et al., 2018). Rainfall dependency on the agricultural sector results in a continuous problem with food security (WFP, 2014). The large majority of the people living in Afar regional state of Ethiopia are pastoralists, deriving their income and subsistence mainly from rearing livestock. According to Famine Early Warning System Network (FEWSNET) report, the humanitarian situation has changed dramatically due to the 2015/2016 drought since the beginning of 2017 in Somali and Afar regions. Thus, the 2015/2016 drought is resulted in large livestock losses and caused severe food insecurity in the pastoral areas of Ethiopia (FEWSNET, 2016).

During drought periods, for example, cereal crop prices increase due to demand-supply imbalance, while livestock prices decrease due to poor body condition and feed scarcity. Studies indicated that the price of main cereal crops increased at the national level during the 1997/98 drought period. Prices of sorghum, wheat, maize, and Teff were 13%, 38%, and 47% higher in the third quarter of 1998 compared to the first quarter of 1997 period (Bachewe et al., 2017). In the 2015 drought period, the price of oxen in January 2017 was 13% lower than that of January 2014, and sheep in January 2017 was 9.4% lower than in January 2014 (Bachewe et al., 2017). According to Ethiopia's Central Statistical Agency (CSA), following the 2015 drought, grain crop production decreased by 13.3% and 15.4% in Afar and Somali pastoralist regions, respectively (CSA, 2018).

Among the numerous drought indices, the most commonly used indices are the Standardized Precipitation Index (SPI) (McKee et al., 1993) and the Standardized Precipitation and Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). The SPI has been increasingly used during the last two decades because of its solid theoretical development, robustness, and versatility in drought analysis and quantification (Quiring, 2009). The SPEI was first proposed as an improved drought index that is especially suited for studies of the effect of global warming on drought severity. Although the steps calculating the SPEI and SPI are similar, the SPEI is based on a climatic water balance that is adjusted using a three-parameter log-logistic distribution (Vicente-Serrano et al., 2010). It is also noted that many researchers have used SPI and SPEI simultaneously to study the impact of drought on crop performance as indicators of drought (Begna, 2020; Mohammed et al., 2022). Drought is the most complicated and least understood of all natural disasters. Its complex and widespread nature makes it difficult to define its beginning and end (Gerber & Mirzabaev, 2019). The application of SPI and SPEI is very important to evaluate drought indices as tools for monitoring, evaluating and testing their ability to explain the variance of crop yield during the growing season. Moreover, it is important that which drought index, SPI or SPEI that more explaining the variance of crop yield over the study area. Therefore, this study aims to assess the past and future variations of drought characteristics and their impact on cereal crop productivity using SPI and SPEI drought indices in Afar region, Ethiopia. Accordingly, we formulated the following research questions to be addressed in this study:

i. How is the spatiotemporal variation of drought characterized during the last 40 years (1981-2020) in the Afar region?
ii. What are the expected changes in drought in the coming decades compared to the base period?
iii. What is the association between drought and rain-fed cereal crop productivity in the study area?

2 MATERIALS AND METHODS

2.1 Description of the study area

The Afar region is located northeast of Ethiopia (Figure 1). The region is geographically located between 8° 51' and 14° 34' N and 39° 47' and 42° 24' E, and has an area of about 94,760 km^2 (Wakie et al., 2014). According to the Ethiopian Economic Association report, the region is divided into five administrative zones (EEA, 2021).

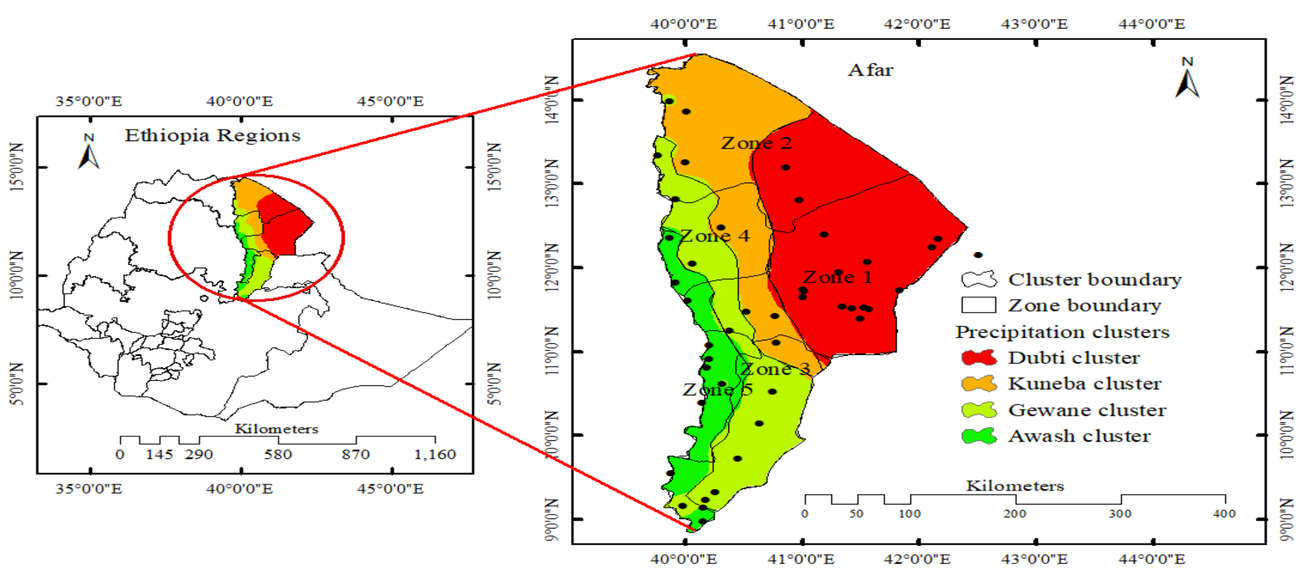

Figure 1| Study area map: spatial distribution of 44 meteorological stations indicated by circled dots that were used in this study. The rainfall stations were first categorized into clusters based on rainfall spatial coherence and clustered into four, namely the Dubti cluster, Kuneba cluster, Gewane cluster, and Awash cluster, using the K-mean clustering approach. Additional data is provided in the attached supplementary materials.

The rainfall of the study area is bimodal, with two wet seasons. The first rainy season extents from February to May (FMAM), known as Belg, while the second and main rain season spans from June to September (JJAS), known as Kiremt, as per the Ethiopian Meteorology Institute (EMI) classification (Aytenfisu, 2024). The Belg rain peaks in April while the Kiremt rains in August (Gummadi et al., 2018). The mean annual rainfall is 740.5 mm, while the mean annual, daily minimum, and maximum temperatures are 28.3, 19.8, and 37.3 °C, respectively (Wakie et al., 2014; Gummadi et al., 2018).

The livelihood of the Afar people is predominantly pastoralism. However, due to recurrent drought, which resulted in a decreasing number of livestock, the pastoral mode of production has been challenged occasionally, and the pastoral households have entered into alternative livelihoods such as agro-pastoralism (Diriba, 2020). According to the CSA report, rain-fed agriculture has been practiced in Afar, and at the moment, a significant portion of households are engaged in crop production in the region. Among cereal crops, Teff, barley, wheat, maize, and sorghum are the most commonly grown crops grown in the region (CSA, 2021).

2.2 Data

We used daily rainfall, maximum, and minimum temperature data from 44 weather stations (> 70% of the total available stations in the Afar region) obtained from the EMI for the period 1981 to 2020 (Figure 1). Since there are gaps in the gauged data, other data sources are utilized to fill the gaps. The missed rainfall data is filled from the Climate Hazards Group Infrared Precipitation (CHIRP). The CHIRP dataset has been used in drought monitoring and evaluations (Tuo et al., 2016; Kebede et al., 2020). The detailed description of the data was provided by Funk et al., (2015) and Dinku et al., (2018). To fill in the daily maximum and minimum temperature data, we used the European Center for Medium-range Weather Forecast's (ECMWF) fifth-generation Atmospheric Reanalysis downscaled at the spatial resolution of 10×10 km^2 (AgERA5). The performance of the data is evaluated over East African countries (Gleixner et al., 2020).

2.2.1 CMIP5 climate projections

The Coupled Model Inter comparison Project phase 5 (CMIP5) dataset provide a quantitative assessment of future drought projection. From the CMIP5 model groups, we used five Regional Climate Models (RCMs) dynamically downscaled for the Coordinated Regional Downscaling Experiments (CORDEX) for the Africa domain. Several scholars in Ethiopia have evaluated these models, and their findings indicate well-simulated rainfall and temperature in Ethiopia (Worku et al., 2018). Details of the models are presented in Table 1.

Table 1| Descriptions of RCMs utilized in this study and their deriving sources.

Description of RCM	**Driving sources**	**Country**	**RCM**
Regional Atmospheric Climate Model version 2.2	EARTH	The Netherlands	RACMOO22T
Swedish Meteorological and Hydrological Institute (SMHI), The Rossby Centre Regional Climate model version 4	CNRM-CERFACS-	Sweden	SMHI-RCA4
Consortium for Small-scale Modeling (COSMO) Climate Limited Area Modelling Community (CLMcom)	CNRM-CERFACS-CNRM-CM5	USA	CCLM4-8-17
Max Planck Institute for Meteorology-Climate Service Center (MPI-CSC), Regional Model	MPI-*M*-MPI-ESM-LR	Germany	REMO2009
Swedish Meteorological and Hydrological Institute (SMHI), version 4	CCCma-CanESM2	Sweden	CanRCA4

The average drought changes concerning the reference period (1981-2005) are computed for the near future (2006-2040), mid-century (2041-2070), and end-century (2071-2100) future projected periods. The three-slice sub-division investigates the possibility of significant variations in drought conditions as applied in literature (Park et al., 2015; Haile et al., 2020). Two Representative Concentration Pathways (RCP4.5 and RCP8.5) emission forcing was selected. These pathways are representative of medium emission (RCP4.5) and higher emission (RCP8.5) scenarios described by Riahi et al., (2011) and Thomson et al., 2011).

2.2.2 Bias correction

The power transformation (PT) method corrects the precipitation bias. This method is often used to correct precipitation data from climate models. It was implemented in Ethiopia and achieved high-quality performance (Tumsa, 2022).

$$P^{cor}\,hst,m,d = P^{b}_{hst,m,d} * \left[\frac{u(P_{obs,m})}{u(P_{hst,m})}\right] \tag{1}$$

Where $P^{cor}\,hst,m,d$ denote the corrected precipitation on the d^{th} day of the m^{th} month and $P_{hst,m,d}$ denote the simulated precipitation outputs during the relevant period, the subscripts d and m are specific days and months, respectively, and u denotes the mean value, b is a random constant number called correction factor.

The maximum and minimum temperatures are corrected using the Linear scaling (LS) bias correction method. The scaling approach is mainly linear and adjusts the climatic factors based on the differences between observed and model output explained by Zollo et al., (2014) and Crochemore et al., (2016).

$$T^{cor}\,\mathrm{hst,m,d} = T_{hst,m,d} + [u(T_{obs,m}) - u(T_{hst,m})] \qquad (2)$$

Where $T^{cor}\,\mathrm{hst,m,d}$ denote the corrected temperature on the dth day of the mth month, and $T_{hst,m,d}$ denote the simulated temperature outputs during the relevant period, the subscripts d and m are specific days and months, respectively, and μ denotes the mean value.

2.2.3 Data clustering

The annual mean precipitation dataset from the 44 stations clusters similar rainfall regimes using a centroid-based approach known as the K-means clustering method. The k-mean algorithm is the most widely used iterative algorithm in data clustering, which iterates to determine the optimal value of the centroid. In the k-mean approach, the ideal numbers of clusters are calculated using a graphical technique called the elbow method noted by Nanjundan et al., (2019) and Umargono et al., (2020). The algorithm's performance improves with a smaller inertia value.

$$J = \sum_{i=1}^{m}\sum_{k=1}^{K} \mathrm{Wik}||\mathrm{Xi} - \mu k||^2 \qquad (3)$$

Where $|Xi - Vj|$ is the Euclidean distance between xi and Vj, k is the number of data points at the ith cluster, m is the number of cluster centers, Xi is the set of data points, and μk is the set of centers, respectively. W$ik = 1$ for data point Xi if it belongs to cluster K; otherwise, $Wik = 0$ and μk are the centroid of Xi's cluster, respectively.

$$\mathrm{Wik} = \begin{cases} 1 \text{ if } k = \mathrm{argmin}, & ||\mathrm{Xi} - \mu k||^2 \\ 0 & \text{otherwise} \end{cases} \qquad (4)$$

In other words, assign the data points Xi to the closest cluster judged by its sum of squared distance from the cluster's centroid.

$$\mu k = \frac{\sum_{i=1}^{m} \mathrm{WikXi}}{\sum_{i=1}^{m} \mathrm{Wik}} \qquad (5)$$

2.2.4 Model performance evaluation

In this study, three statistical parameters are implemented to evaluate the performance of regional climate models performance whether they are reproducing the observed past climate variables over the period of 1981 to 2005. The statistical metrics in this study are comprising Pearson Correlation, Mean Root Square error (MRSE) and Bias (BIAS), respectively. The RMSE measures the absolute mean difference between the observed and simulated dataset, where the value of RMSE is closer to zero, it is well scored (Chai et al., 2014). The Pearson correlation measures the linear relationship between two variables, which is used to evaluate the performance of RCMs in simulating the local climatic variables. Boslaugh (2012) states that the correlation coefficient (r) ranges from -1 to +1 when the value of r is 0.1 is taken as small, 0.3 is taken as medium, and 0.5 is taken as high model performance. The Pearson correlation coefficient is computed as:

$$r = \frac{\sum_{i=1}^{n}(O-\overline{O})(M-\overline{M})}{\sqrt{\sum_{i=1}^{n}(O-\bar{O})^2} * \sqrt{\sum_{i=1}^{n}(M-\bar{M})^2}} \quad (6)$$

Where r is the correlation coefficient, O is observed rainfall, $\overline{O}$ is observed rainfall, M is model rainfall, and $\overline{M}$ is the mean of model rainfall. The Bias measures the systematic error between the observed and simulated climate variables, and when the value close to zero, indicating good performance of the model, while values away from zero, the models deviate from the observations. When the value is negative, indicate the models are underestimating while the value is positive, the models are overestimating (Florida, 2021).

$$BIAS = \frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N} O_i} \quad (7)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(S_i - O_i)^2}{N}} \quad (8)$$

Where S and O are the simulated and observed values, respectively, while i refers to the simulated and observed pairs and N is the total number of such pairs.

2.2.5 Crop yield data

Drought is a major factor influencing cereal crop production and productivity in most of the rain-cultivated areas across Ethiopia. So, it is interesting to analyze how current drought indices are associated with the cereal yields in the region. As a result, the average cereal yields provided by the CSA, (2019) for 1994-2019 period, and reported as a growing period yield sum for entire Afar region (CSA, 1996). As the Kiremt (June-September) cropping season is the main cereal crop production season, we focused on this cropping season in our study. The cereal crops we considered are mainly the total sum of maize, teff, and sorghum, as these are staple foods of the region.

2.3 Methods

In this study, we implemented the SPI and SPEI meteorological drought indices to evaluate the characteristics of drought and its impact on crop yield. The indices are calculated using the Climate Data Tool (CDT). As mentioned by Nsengiyumva et al., (2021) and Dinku et al., (2022), CDT is an open-source, R-based software with an easy-to-use graphical user interface used by over 20 countries.

2.3.1 Standardized precipitation index

To assess long-term and medium-term drought occurrences, the SPI value and its probability density function of the gamma distribution are calculated as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}}, \text{for } x > 0 \quad (9)$$

Where α > 0 is a shape parameter, β > 0 is a scale parameter, x > 0 is the amount of precipitation, and (α) is the gamma function. The probability that the random variable x is less than x_0 can be computed for the precipitation x_0 in a certain year:

$$F(x < x_0) = \int_0^{\infty} f(x)\, dx \quad (10)$$

$$F(x = 0) = \frac{m}{n} \quad (11)$$

Where m is the number of samples with precipitation of 0 and n is the total number of samples. To normal standardized processing of Γ probability distribution, we have substituted the result of probability value into the normalized normal distribution function:

$$F(x < x_0 = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-x^2/2} dx \quad (12)$$

The SPI can easily be obtained as the standardized values of F(x) and calculated as:

$$SPI = S \frac{t-(c_2 t + c_1) + c_0}{[(d_3 t + d_2)t + d_1]t + 1} \quad (13)$$

Where $t = \sqrt{ln \frac{1}{F^2}}$ and $c_0 = 2.515517, c_1 = 0.802853, c_2 = 0.010328, d_1 = 1.432788$

$d_2 = 0.189269 \; and \; d_3 = 0.001308$, respectively. Where S is the probability density plus or minus coefficient. If F > 0.5, then $S = 1$, if F ≤ 0.5, then $S = -1$.

2.3.2 Standardized precipitation and evapotranspiration index

SPEI is calculated similarly based on the difference between potential Evapotranspiration (PET) and Precipitation (P). This study used the modified Hargreaves method based on only observed temperature values (Hargreaves & Allen, 2003). The difference between P and PET is computed as follows

$$D_i = P_i - \text{PET}_i \quad (14)$$

$$\text{PET} = 0.0023(Tmax - Tmin)^{0.5} * (Tmean + 17.8) * Ra \quad (15)$$

Where PET is potential evapotranspiration (mm day^{-1}), $Tmax$, $Tmin$, and $Tmean$ are maximum, minimum, and mean air temperature (°C).

R_a is extraterrestrial radiation given in (mm day^{-1}), computed from latitude and the day of the year

$$\text{Ra} = \frac{1440}{\pi}(\text{Gsc.Dr})[\varphi \text{sign}(\varphi)\sin(\sigma) + \cos(\varphi)\cos(\sigma)\sin(\varphi s)] \quad (16)$$

$Gsc = 0.0820 \text{MJ m}^{-2}$, is solar constant

$$Dr = 1 + 0.022\cos\left[\frac{2\pi(JD)}{365}\right] \text{ is the inverse relative distance from the Earth to the Sun} \quad (17)$$

$JD \; is \; a \; day \; of \; the \; year$

$$\varphi s = arcos[-\tan(\varphi)\tan(\sigma)] \text{ is the sunset hour angle (rad)} \quad (18)$$

$$\sigma = 0.409\sin(2\pi\frac{JD}{365} - 1.39) \text{, is the solar declination (rad)} \quad (19)$$

φ is the latitude of the location

$$\frac{MJ}{m^2 d}, \quad \text{can be converted to mm/d: as } \frac{mm}{d} = \frac{1}{2.43} * \frac{\frac{MJ}{m^2}}{d}$$

Di is quantified at different time scales using the same procedure as SPI. The difference between the specific months j and year i depends on the selected time scale k. For example, the accumulated difference for j month in a given year i with k-month time scale is calculated using the formula:

$$X_{i,j}^{k} = \sum_{I=k+i,\ \ k+j}^{k} D_{i-I,j} + \sum_{I=1}^{j} D_{i,j\ ,} \text{ if j < k} \quad (20)$$

$$X_{i,j}^{k} = \sum_{I=j-k+j}^{k} D_{i,j,} \ \text{ if j} \geq \text{k} \quad (21)$$

Where $D_{i,j}$ is the difference between P and PET of the first month of the year i, given in mm. The three parameters of the log-logistics probability density function are used to fit the data series and expressed as follows:

$$f(X) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \quad (22)$$

Where α, β, and γ represent the scale, shape, and location parameters, respectively, that are estimated from the data series Di. Parameters of the log-logistic distribution obtained by the L-moment procedure that is the most robust and easy approach Reath et al., (2018).

$$\beta = \frac{2\text{w}1-\text{w}0}{6\text{w}1-\text{w}0-6\text{w}2} \quad (23)$$

$$\alpha = \frac{(\text{w}0-2\text{w}1)\beta}{\left(1+\frac{1}{\beta}\right)\left(1-\frac{1}{\beta}\right)} \quad (24)$$

$$\gamma = w0 - \alpha\Gamma\left(1+\frac{1}{\beta}\right)\Gamma \quad (25)$$

Thus, the cumulative distribution function of a given time scale is computed as follows:

$$F(\text{x}) = \left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-1} \quad (26)$$

The SPEI can easily be obtained as the standardized values of F(x) and calculated as:

$$\text{SPEI} = \text{w} - \frac{\text{C}_0+\text{C}_1\text{W}+\text{C}_2\text{W}^2}{1+\text{d}_1\text{w}+\text{d}_2\text{w}^2+\text{d}_3\text{w}^3} \quad (27)$$

$$\text{w} = \sqrt{-2\ln(\text{P})}$$

$\text{C}_0 = 2.51517, \text{C}_1 = 0.802853$, $\text{C}_2 = 0.0103288$, $\text{d}_1 = 1.432788$, $\text{d}_2 = 0.189269$, and $\text{d}_3 = 0.001308$ and P is the probability of exceeding a determined D_i value, $\text{p} = 1 - \text{F}(x)$ if p > 0.5, then p is replaced by $1 - \text{p}$ and the sign of the resultant SPEI is reversed. Guttman, (1999) Guttman, (1999) and Vicente-Serrano et al. (2010) categorized the drought characteristics into different severity levels, as indicated in Table 2. The authors also defined the drought event criteria for any time scale. The number of months in which SPI/SPEI values are consecutively ≤ -1 is considered a drought incident and determines the duration of the incident. The drought event ends when the SPI/SPEI becomes positive. Therefore, each drought event has a duration defined by its beginning and end and an intensity for each month the event continues. The positive sum of the SPI/SPEI within a drought event is known as drought magnitude (WMO, 1987).

Table 2| SPI and SPEI drought categories defined by drought severity regimes

Anomaly	Range of SPI/ SPEI values (d_value)	drought severity regime
Positive	2.0 < d_value <= MAX	Extremely wet
	1.5 < d_value < = 2.0	Very wet
	1.0 < d_value <= 1.5	Moderately wet
None	-1.0 < d_value <= 1.0	Normal precipitation
Negative	-1.5 < d_value <= -1.0	Moderately dry
	-2.0 < d_value <= -1.5	Very dry
	MIN <= d_value <= -2.0	Extremely dry

The SPI is considered to enumerate the rainfall deficit for multiple timescales. These time scales reveal the impression of drought on the accessibility of the different water resources. We selected the 3-month and 12-month time scales of SPI and SPEI to evaluate past and future drought occurrence for the following reasons. The 3-month SPI/SPEI reveals medium-term moisture conditions of the current month and the past two months, providing a seasonal rainfall estimation for seasonal crop production. The 12-month period reflects the long-term rainfall patterns that compare the rainfall for 12 consecutive months with that recorded in the same 12 consecutive months in all previous years without missing data (WMO, 1987).

2.3.3 Drought trend

The Mann-Kendal (MK) test is used to perceive statistically significant decreasing or increasing trends in long-term temporal datasets by Mann, (1945) and (Wang & Vrijling, (2005). The MK trend test is based on two hypotheses: one is null (Ho), and the other is the alternative (H1) hypothesis. The Ho expresses the existence of no trend, while H1 elucidates a significant rising or declining trend in the temporal drought pattern. Based on the 5% significant level, if the p-value is < 0.05, the alternative hypotheses are accepted, which signifies the presence of a trend in the data. If the p-value is > 0.05, the null hypothesis will be accepted, which denotes the absence of a trend in the data. The following equations provide the computational steps for the trend.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sin(T_j - T_i) \quad (28)$$

Where T_j and T_i are the monthly, seasonal, and annual values in years' j and i, j > i respectively, n is the number of data points. Assuming $(T_j - T_i) = \theta$, the value of sign (θ) is computed as follows:

$$\sin(T_j - T_i) = \begin{cases} 1; & if \quad Tj - Ti > 0 \\ 0; & if \quad Tj - Ti = 0 \\ -1; & if \quad Tj - Ti < 0 \end{cases} \quad (29)$$

A positive value of S indicates an increasing trend, whereas a negative value indicates a declining trend in the data. The magnitude of drought is evaluated by a simple non-parametric procedure using Sen's slope estimator developed by Sen (1968) and calculated as follows:

$$Q_i = \left(\frac{x_j - x_i}{j-1}\right) \quad (30)$$

Where i = 1 to n-1, j = 2 to n, $\mathbf{x}_j$ and $\mathbf{x}_i$ are data values at time j and i where (j > i), respectively. If there are n values of $\mathbf{x}_j$ in the time series, Sen's slope estimator will be N = n(n-2)/2. The Sen's slope estimator is the mean slope of N values; then, the Sen's slope is estimated as:

$$Q_{ij} = \begin{cases} \frac{x_j - x_i}{j-1}; & if\ n\ is\ odd \\ \frac{1}{2}\left(Q\,\frac{N}{2} + Q\left[\frac{N+2}{2}\right]\right); & if\ n\ is\ even \end{cases} \quad (31)$$

The positive value of $\mathbf{Q_{ij}}$ indicates an increasing trend, while the negative value of $\mathbf{Q_{ij}}$ shows a decreasing trend, where the units of Sen's slope ($\mathbf{Q_{ij}}$) is the slope per year in the temporal dataset.

The MK trend test is a nonparametric test widely used to detect significant trends in a set of time series data. However, researchers have shown that the original Mann-Kendall test did not consider serial correlation in a time series data set Hirsch, (1981) and Bari et al., (2016). Furthermore, in many real-world situations, observed data are autocorrelated, which can lead to misinterpretation of the results of trend estimates (Cox et al., 2013; Hamed & Rao, 1998). Consequently, Hamed & Rao, (1998) have developed a modified Mann-Kendall trend test that is based on the assumption that time series data are serially correlated and therefore autocorrelation is addressed by a modified MK trend test. The modified MK trend test has been used by many researchers to eliminate the influence of serial correlation in the original MK trend test in time series trend detection studies Yue & Wang, (2015) and Patakamuri & Brien, (2021). In this study, we use the modified MK trend test developed by Hamed & Rao, (1998).

2.3.4 Drought and crop yield correlation

Climate variability seriously threatens the productivity of Ethiopia's food crops. Understanding the impact of extreme weather events on agricultural production is crucial for resilience to climate change and improving food security. To determine the context and magnitude of drought-induced yield fluctuations, it is necessary to eliminate or minimize the influence of non-climatic factors such as variety, management, and technology to eliminate biases arising from these trends. Crop yield anomalies are identified from declining time series using a linear regression method, and drought indices are linked to yield anomalies. Several researchers have used a linear regression model to modify yield trends and used the resulting anomalies to determine the effects of drought on crop yield by Lobell & Asner, (2003) and Potopova et al., (2016). A simple linear regression model is given as follows:

$$Y_t = \alpha + \beta * X_t \qquad (32)$$

Where Y_t represents a yield anomaly at time t, α represents the constant, which is called the intercept of the regression model, $and\ \beta$ is a regression coefficient of the independent variable, which represents the gradient of the line and is referred to as the slope. X_t is an independent variable.

The association between de-trended yield and drought indices is explored through correlation analysis using a statistical package for social studies (SPSS). The correlation results provide initial information on the positive or negative associations, which helps to understand the regression results. Finally, a linear regression analysis of the de-trended yield and drought indices is performed to quantify the percentage response of determinant (r^2) of yield variations achieved jointly by SPI and SPEI at a 4-month time scale. The yield anomalies (Y_t) at time t are calculated as follows:

$$Y_t = \mathrm{y} - \mu \qquad (33)$$

The crop data is regional yield data (quintal per hectare, qt/ha) for the entire Afar region for the Kiremt cropping season from 1994 to 2019. Since the climate of the study area is bimodal, FMAM and JJAS, the SPI and SPEI at a 4-month time scale are used to evaluate the impact of drought on crop yield.

2.3.5 Assessing drought characteristics

Drought characteristics can be expressed by these essential features such as duration, frequency, magnitude, intensity, severity, spatial-temporal room by Ettenmaier, (2005) and Alamgir et al., (2015). The duration, severity, intensity and frequency of the drought events were computed based on Table 2. The frequency of the drought is the number of months in which the SPI/SPEI value agrees as a set value in Table 2 and divided by the number of months in the whole sequence (Wang et al., 2014).

$$F = \frac{n}{N} * 100 \quad (34)$$

Where n is the number of months of drought events when the SPI/SPEI is less than - 1 that a drought index value agrees a set of drought criterion divided by the number of months in the whole series (N). The drought frequency (F) is used to assess the drought prevalence during the study period over the region. The drought duration is the length of drought period. Whereas the drought magnitude (M) is the cumulative sum of the drought index value based on the duration of the drought occurrence when the SPI/SPEI value is less than or equal to -1 and computed as:

$$M = \sum_{i \le -1}^{D} SPI/SPEI \quad (35)$$

Similarly, the intensity of a drought (I) is the ratio of drought magnitude (M) to drought duration (D), respectively. Events that have a shorter duration and higher magnitude will have larger intensities.

$$I = \frac{M}{D} \quad (36)$$

Moreover, the inverse distance weighting approach is implemented to visualize and interpolate the spatial patter of drought characteristics with the support of ARC-GIS tool.

3 RESULTS

3.1 Temporal pattern of drought

Time series plots of drought indices are derived from station-wide and spatial averages of 44 meteorological stations' precipitation and temperature datasets for the 1981-2020 period. The average change in drought magnitude and frequency under global warming is investigated using five RCMs of daily precipitation and temperature datasets to understand how frequently the drought will likely occur. The drought characteristics, such as frequency and intensity, are used to evaluate the occurrence of drought over the study area using SPI and SPEI at 3-month and 12-month time scales. Furthermore, the drought index for the crop growing season is calculated based on the seasonal classification of the study area, which mainly includes Belg and Kiremt crop growing seasons. Therefore, SPI and SPEI at a 4-month time scale are used to evaluate the impact of drought on crop yield.

Figure 2 depicts the spatially averaged time series plot of SPI and SPEI at 3- and 12-month time scales for the 1981-2020 period. The finding shows that severe drought prevailed in 1984, 1987, 1994, 1999, 2002, 2007, 2008, 2009, and 2015, whereas extreme drought prevailed in 2016. These years are considered the most intense drought episodes, with a severity scale of -1.50 to -5.35. 1984, 2008, 2009, and 2015 are considered the driest years across all locations. The drought intensity quantified by the SPEI 3-month and SPEI 12-month time scales were -1.36 and -1.47, with the extreme drought of -2.17 and -2.01; this extreme drought was quantified in 1984 and 2015, respectively. Whereas the drought intensity quantified by SPI 3-month and SPI 12-month time scales were -1.50 and -1.77 with extreme drought of -3.15 and -2.8, this extreme drought was evaluated for 1984 (Figure 2).

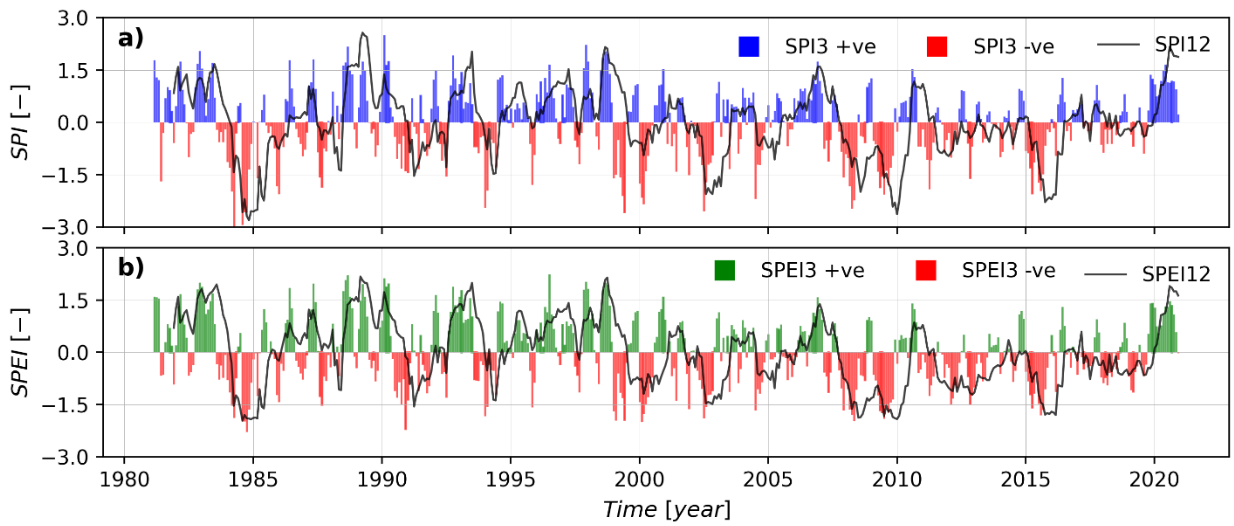

Figure 2| Spatial averaged time series plot for SPI (a) and SPEI (b) at a 3-month (bar-plots) and 12-month (line-plot) time scale. Blue (SPI) and green (SPEI) colors represent positive values, and red represents negative values.

The SPI and SPEI values at 3-month and 12-month time scales at cluster representative stations (Figure 1) are presented in Figure 3 and Figure 4. The results indicate the presence of severe to extreme drought conditions. For instance, extreme drought quantified by SPI 3-month time scale at Argoba (-4.49 for 2015), Dubti (-2.11 for 2015), Gewane (-4.03 for 2017) and Kuneba (-3.54 for 2015). At the same time, extreme drought quantified by SPI-12-month time scale for the stations were -4.50, -2.98 -2.57, and -4.01, calculated for 2015, 1999, 1984, and 2015, respectively (Figure 3).

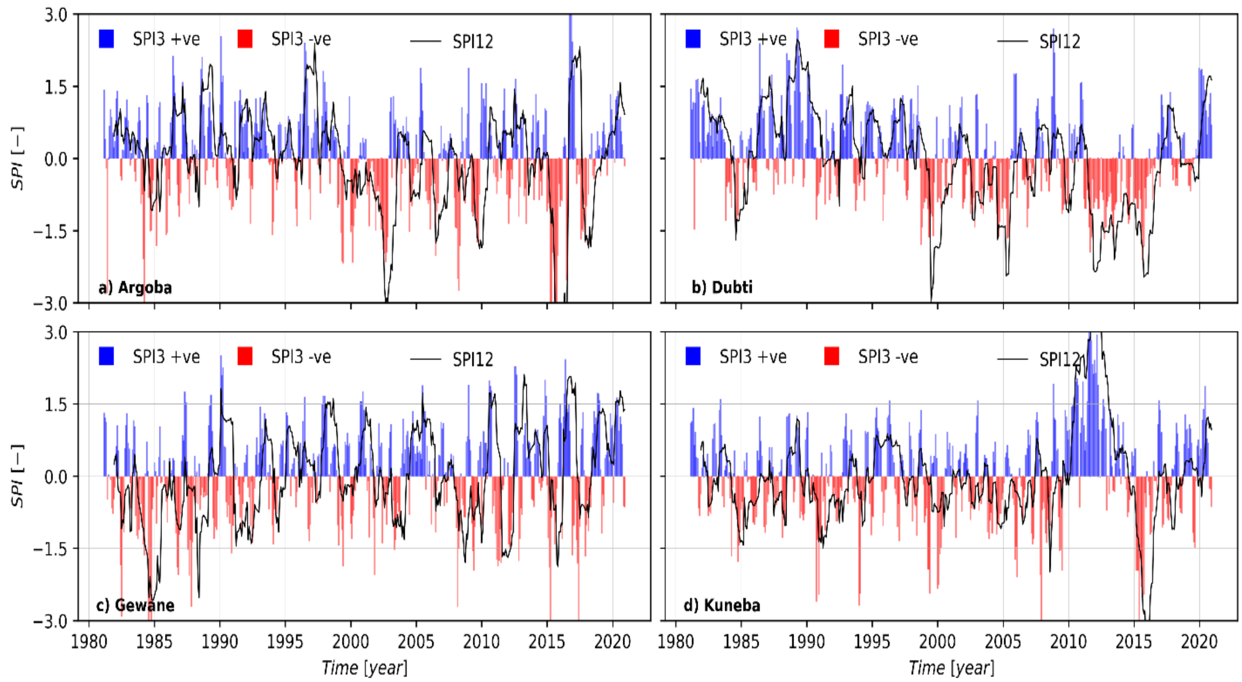

Figure 3| Time series plot for Argoba (a), Dubti (b), Gewane (c), and Kuneba (d) stations at SPI's 3-month (bar-plots) and 12-month (line-plots) time scales. Blue colors represent positive values, and red represents negative values.

Similarly, extreme drought was quantified by the SPEI 3-month time scale at Argoba (-2.60 for 2009), Dubti (-2.20 for 2015), Gewane (-3.33 for 2015), and Kuneba (-3.08 for 2009) stations. Extreme drought quantified by the SPEI 12-month time scale at the same stations was -2.27, -2.01, -2.21, and -5.35, computed for 2016, 2008, 2015, 2011, and 2008, respectively (Figure 4).

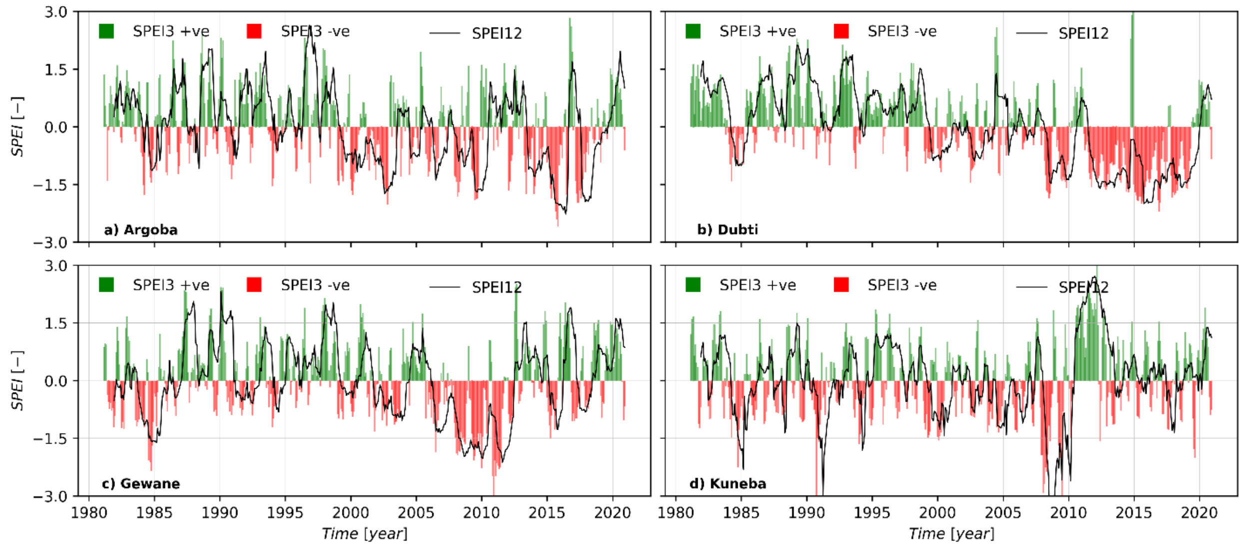

Figure 4| Time series plot for Argoba (a), Dubti (b), Gewane (c), and Kuneba (d) stations at SPEI's 3-month (bar-plots) and 12-month (line-plots) time scales. Green colors represent positive values, and red represents negative values.

3.2 SPI and SPEI drought indices

Table 3 presents the drought frequency and intensity for SPI and SPEI at 3-month and 12-month time scales. The spatial averaged time series findings indicated that SPEI identifies drought more frequently than SPI at both medium and longer scales. For example, the drought frequency identified by SPEI at 3-month and 12-month scales is 17.8% and 16.0%, respectively. At the same time, the drought frequency identified by SPI at the 3-month and 12-month scales is 16.6% and 13.2%, respectively. The drought intensity quantified by SPI 3-month time scale at Argoba, Dubti, Gewane, and Kuneba stations were -1.6%, -1.2%, -1.4%, and -1.5%, respectively. Whereas the drought intensity quantified by SPI, 12-month time scale at the same stations were -2.0%, -1.6%, -1.4%, and -1.8%, respectively. Similarly, the drought intensity quantified by the SPEI 3-month time scale at Argoba, Dubti, Gewane, and Kuneba stations was -1.5%, -1.5%, -1.5%, and -1.4%, respectively. At the same time, the drought intensity quantified by the SPEI 12-month time scale at the same stations were -1.5%, -1.4%, -1.5%, and -1.8%, respectively (Table 3).

The station drought frequency analysis indicated frequent droughts over the study area with varying severity during the last 40 years. For example, the drought frequency identified by the SPI 3-month time scale at Argoba, Dubti, Gewane, and Kuneba stations was 15.9%, 14.0%, 18.4%, and 15.1%, respectively. At the same time, the frequency of drought identified by the SPI 12-month time scale at the same station was 13.7%, 18.8%, 16.5%, and 13.2%, respectively. Similarly, the drought frequency identified by SPEI at a 3-month time scale at Argoba, Dubti, Gewane, and Kuneba stations were 16.8%, 17.2%, 14.0%, and 16.1%, respectively. At the same time, the drought frequency identified by the SPEI 12-month time scale at the stations mentioned above were 16.7%, 20.2%, 16.5%, and 13.7%, respectively (Table 3).

Table 3| Drought frequency [%] and intensity [%] calculated for SPI and SPEI at 3-month and 12-month time scales.

Station	Frequency [%]				Intensity [%]				Extreme drought months
	SPI 3	SPEI 3	SPI 12	SPEI 12	SPI 3	SPEI 3	SPI 12	SPEI 12	
Argoba	15.9	16.8	13.7	16.7	-1.6	-1.5	-2.0	-1.5	
Dubti	14.0	17.2	18.8	20.7	-1.2	-1.5	-1.6	-1.4	
Gewane	18.4	14.0	16.5	16.5	-1.4	-1.5	-1.5	-1.5	
Kuneba	15.0	16.1	9.4	13.7	-1.5	-1.4	-1.6	-1.8	
Spatial average	16.5	17.8	13.2	16.0	-1.5	-1.4	-1.8	-1.5	

The correlation and regression analysis are used to associate the relationship between SPI and SPEI at 3-month, 6-month, 12-month and 24-moth time scale. For the comparison of both indices, correlation Heatmaps and scatter plotting are presented in supplementary**Error! Reference source not found.**Figures 4 and 5, and statistically evaluated by using the coefficient of determination and correlation coefficient. The SPI and SPEI calculated at different time scales are strongly correlated ($r > 0.7$) at a 0.05 significant level, indicating a fair degree of agreement between the two indices. The regression result indicated that strongest fit has been shown by values of SPI and SPEI at 6-month time scale, with R-squared value of 91.20% of the variation. Moreover, the value of SPI gives closer result with SPEI in the same time scale (Supplementary Figure 5**Error! Reference source not found.**). According to Supplementary Figure 5, the highest value of R-square is 0.912 for SPI and SPEI at 6-month time scale while the lowest is 0.8724 for SPI and SPEI at 24-month time scale.

3.3 Spatial characteristics of drought

The spatial extent of drought frequency, duration, and magnitude was calculated by inverse distance weighted (IDW) interpolation method for SPEI at 3-month and 12-month time scales (Figure 5). The most frequent drought prevailed at Chifra, Gewane, Dalifagi, and Telalak stations, where the drought frequency ranged from 17.3% to 19.9% during the 1981-2020 period for a 3-month time scale. Whereas for the 12-month time scale, the maximum drought frequency prevailed at Semera, Dubti, Elidar, Mille, Chifra, Awura, Bidu, and Melkasedi stations with drought frequency in the range of 18.4% to 21.2% (Figure

5a,b). The drought duration at the 3-month time scale shows that longer duration prevailed at Chifra, Gewane, Telalak, Dubti, Ewa, and Argoba stations with a drought length of 81 to 95 months over the 1981-2020 period. Whereas at a 12-month time scale, the longer drought duration was quantified at Dubti, Awura, Gewane, Mille, Dawe, Semera, and Chifra stations, ranging from 83 to 99 months, respectively (Figure 5 c, d). Drought magnitude showed that more intense drought quantified at Dalifagi, Gewane, Telalak, Chifra, Awura, Ewa, Teru, and Yalo meteorological stations with magnitude in the range of 117.3 to 162.6 for a 3-month time scale. At the longer time scale, more intense drought was calculated at Dalifagi, Gewane, Dubti, Awura, Assaita, Dawe, Mille, and Semera stations with magnitude in the range of 122.6 to 242.7 throughout 1981 to 2020, respectively (Figure 5 e,f).

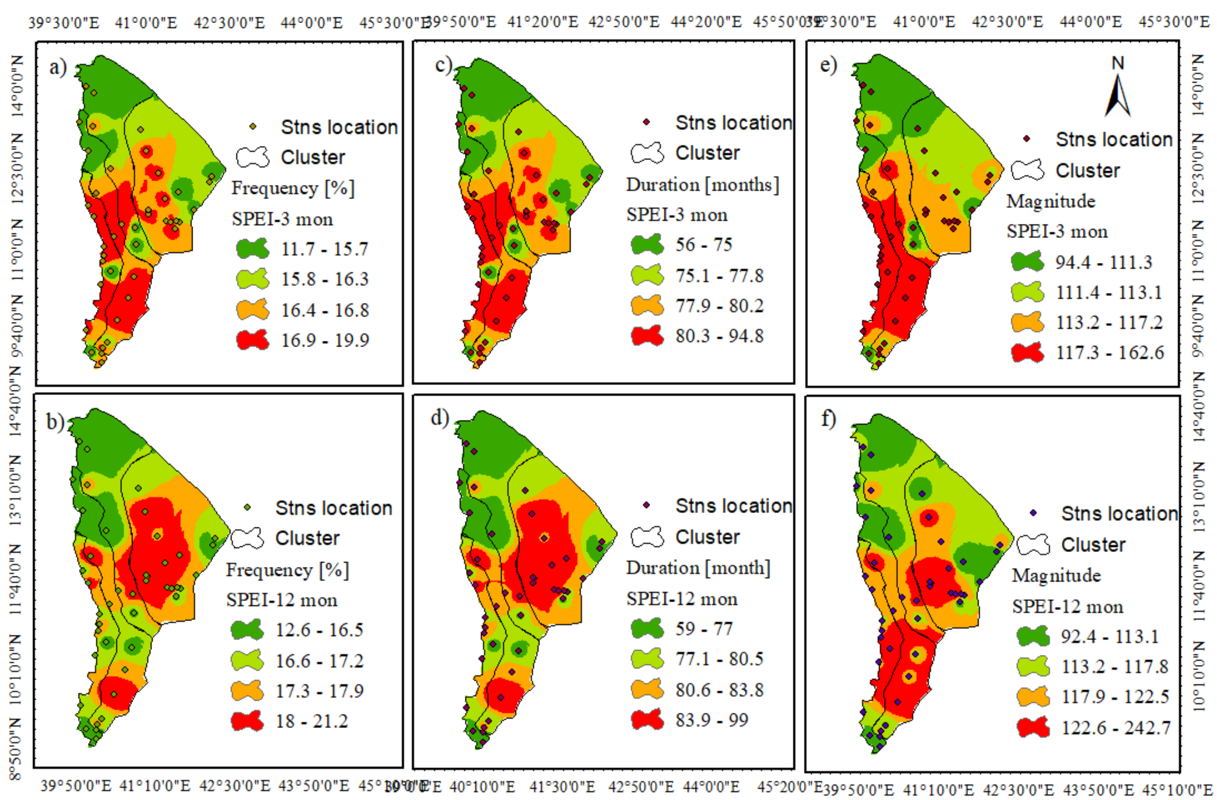

Figure 5| Drought frequency [%] (left panel), duration [months] (middle panel), and magnitude [%] (right panel). The upper row shows the SPEI 3 months, and the lower row shows the SPEI 12-month scale.

Figure 6 presents the number of stations [%] that showed drought during the 1981 to 2020 period for Belg (February to May) and Kiremt (June to July) farming seasons. All 44 meteorological stations showed drought occurrence in 1984 for both seasons. For the 1984, 2008, 2009, and 2015 years, the Belg drought propagated to Kiremt for nearly all the stations **(**Figure 6).

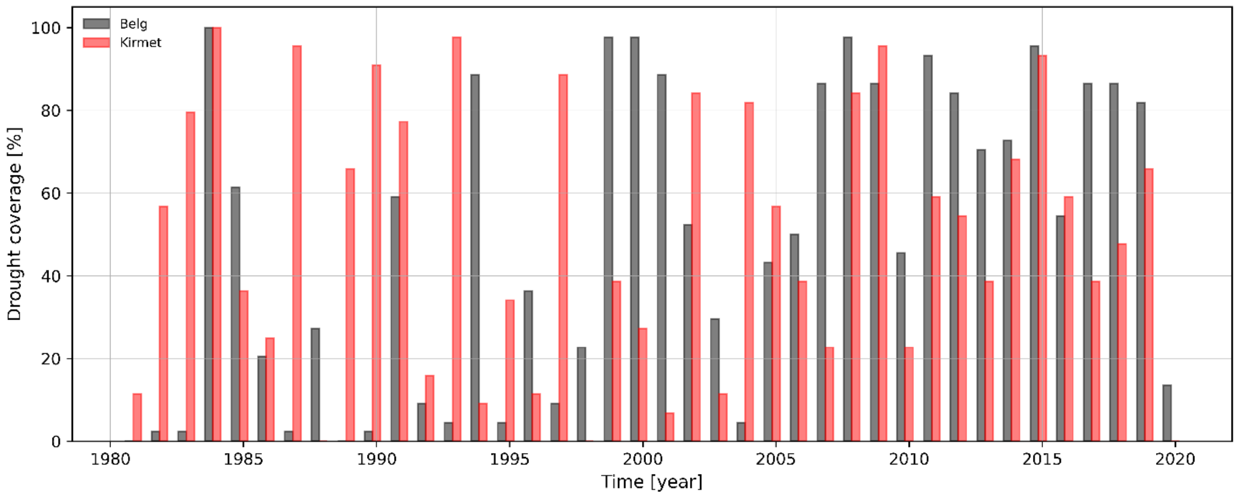

Figure 6| Number of stations [%] that recorded drought during the Belg and Kiremt farming seasons for the 1981-2020 period. Black and red represent drought during Belg and Kiremt seasons, respectively. The most widespread drought coverage prevailed during the Belg cropping season, particularly after 1999 (Figure 6).

Table 4 Presents drought trends and magnitudes throughout 1981-2020 period which shows how drought is severe during Belg and Kiremt cropping season at climate station. The modified MK and Sen's slope Estimator were used to determine trend and magnitude, respectively under the SPEI 4-month time scale. During the Belg crop growing period, 41 stations demonstrated a negative trend. Among the 41 stations, 17 indicated significantly increasing trend toward dryness, with magnitude of in the range -1.25 to -10.0. The strong magnitude was recorded in Dubti, Abala, Gedamaitu, Awash-7 kilo, Semera Afambo, Afdera, Dalifagi, Dawe, Berhaile, Megale, Mille with magnitude of in the range -3.75 to -10.0. Similarly, the drought characteristics during Kiremt crop growing period indicated low significant as compared to Belg crop growing period. Among 44 investigated stations, only 15 stations indicated increasing trend toward dryness, with magnitude ranging from -2.21 to -12.5. The strongest magnitude recorded at Afambo station and have a Sen's slope magnitude estimator of -12.5. The table also shows that there was no significant increasing or decreasing trend at any of the climate stations during Kiremt season. Moreover, the drought indices over the study area revealed no significant trends nearly all of the stations in Kiremt period (Table 4).

Table 4| Drought trend during Belg and Kiremt farming seasons under SPEI-4 month time scale.

No	Stations	Belg				Kiremt			
		Kendall's tau	S'	p-value	Sen's slope	Kendall's tau	S'	p-value	Sen's slope
1	Abala	-0.444	-16	0.0153	-9.5	0.000	0	0.000	3.25
2	Adaitu	0.111	4	0.6265	1.75	0.333	12	0.300	1.25
3	Afambo	-0.444	-16	0.0153	-7.75	-0.333	-12	0.144	-8.25
4	Afdera	-0.444	-16	0.0117	-8.25	-0.167	-6	0.396	-1.75
5	Argoba	-0.278	-10	0.2291	-2.5	-0.111	-4	0.566	-1.75
6	Asara	-0.167	-6	0.3559	-3.75	0.389	14	0.166	4.5
7	Assaita	0.167	6	0.3958	4	0.222	8	0.450	4
8	Awaramelka	-0.056	-2	0.8383	-2	0.500	18	0.070	0.574
9	Awasharba	-0.222	-8	0.3020	-8.5	-0.056	-2	0.838	-0.5
10	Awashsebat	-0.389	-14	0.0166	-4.25	-0.111	-4	0.675	-3
11	Awashsheleko	-0.111	-4	0.5661	-4.25	-0.056	-2	0.838	-4.25
12	Awura	0.000	0	1.0000	-1	0.000	0	0.000	5.75
13	Berhaile	-0.389	-14	0.0097	-4.5	0.056	2	0.882	2.5
14	Bidu	-0.278	-10	0.2291	-3.5	-0.056	-2	0.838	-1.63
15	Bure	-0.389	-14	0.0139	-5.25	0.222	8	0.450	3.5
16	Chifra	-0.167	-6	0.3958	-1	0.056	2	0.854	1
17	Dalifagi	-0.222	-8	0.0256	-4.5	0.389	14	0.214	2.75
18	Dawe	-0.278	-10	0.0289	-4.5	0.056	2	0.838	0.25
19	Ditchoto	-0.333	-12	0.1886	-6.75	-0.056	-2	0.865	0
20	Dobi	-0.111	-4	0.6265	-2.25	0.333	12	0.144	3
21	Dubti	-0.667	-24	0.0414	-10	-0.222	-8	0.288	-3
22	Elidar	-0.278	-10	0.2061	-4.5	0.000	0	0.000	0
23	Elwiha	-0.222	-8	0.4280	-4.75	0.222	8	0.256	6.75
24	Endifo	-0.167	-6	0.3958	-5	0.389	14	0.139	4
25	Erebti	-0.167	-6	0.5403	-3.75	0.444	16	0.089	5.75
26	Ewa	-0.389	-14	0.0126	-5	0.222	8	0.352	4.5
27	Galafi	-0.222	-8	0.2876	-3.5	0.167	6	0.396	3.25
28	Gedamaitu	-0.611	-22	0.0094	-9.5	-0.222	-8	0.239	-1.5
29	Gerjele	-0.278	-10	0.0181	-6.5	0.056	2	0.838	2
30	Gewane	-0.278	-10	0.2888	-3	0.278	10	0.181	4.5
31	Harsis	-0.056	-2	0.8535	-3.25	-0.056	-2	0.854	-0.5
32	Kasagita	-0.389	-14	0.0126	-8.25	0.000	0	0.000	1.5
33	Kuneba	-0.222	-8	0.2389	-1.25	0.111	4	0.614	3.25
34	Logia	-0.111	-4	0.5661	-7.5	0.111	4	0.667	2
35	Manda	-0.278	-10	0.2505	-4.5	0.167	6	0.429	1.25
36	Megale	-0.111	-4	0.0054	-4	0.056	2	0.854	1.75
37	Melkasedi	-0.333	-12	0.0153	-6.25	-0.222	-8	0.302	-1.75
38	Mille	-0.167	-6	0.3958	-3.75	0.278	10	0.289	5.25
39	Semera	-0.333	-12	0.0153	-8.25	-0.111	-4	0.566	-3.25
40	Serdo	-0.389	-14	0.1658	-6.5	-0.222	-8	0.302	-0.75
41	Slisa	-0.278	-10	0.0155	-2.25	-0.167	-6	0.396	-1.25
42	Telalak	-0.167	-6	0.3958	-3	0.167	6	0.396	2.25
43	Teru	-0.167	-6	0.4577	-1.75	0.000	0	0.000	0
44	Yalo	-0.056	-2	0.8651	-0.5	0.000	0	0.000	0.75

3.4 Future drought frequency and magnitude projections

Dubti and Awash meteorological stations are selected to project future drought occurrence over the study area. The two stations are here used as reference climate stations due to the available historical dataset to evaluate historical climate model performance. As indicated in Figure 1, the two stations are located at lower elevation (Dubti station) at Dubti cluster and higher elevation (Awash station) at Awash cluster in the available stations network. Figure 7| Drought frequency [%] at Dubti and Awash stations under RCP 4.5 and 8.5 climate scenarios for the near-term (2006-2040), mid-term (2041-2070), and end of the century (2071-2100).

presents drought frequency at Dubti and Awash stations under RCP 4.5 and 8.5 forcing scenarios. We select the two stations because of better observational data records (>81%) and representativeness of the high (Awash) and low (Dubti) precipitation distribution of the Afar region. The result indicated that more intense drought is likely in both climate-forcing scenarios in the middle and end of the century. For instance, the average change (compared to the baseline period) in drought frequency under RCP4.5 is likely to increase by 2.7% and 8.3% (near future), 8.2% and 33.2% (mid-century), and 11% and 44.8% (end of the century) at Dubti station. Under the same climate forcing, the drought frequency is likely to increase by 12.2% and 10.1% (near future), 35.3% and 53.2% (mid-century), and 33.2% and 30.3% (end of this century) at Awash station. The average change in drought frequency under RCP8.5 forcing scenarios is likely to increase by 2.6% and 2% (near future), 12.9% and 12.8% (mid-century), and 38.7% and 73.2% (end of the century) at Dubti station. For Awash station, the average change in drought frequency is likely to increase by 11.9% and 6.9% (near future), 16.1% and 18.2% (mid-century), and 50.7% and 54.4% (end of the century) as calculated for SPEI 3- and 12-months scale (Figure 7).

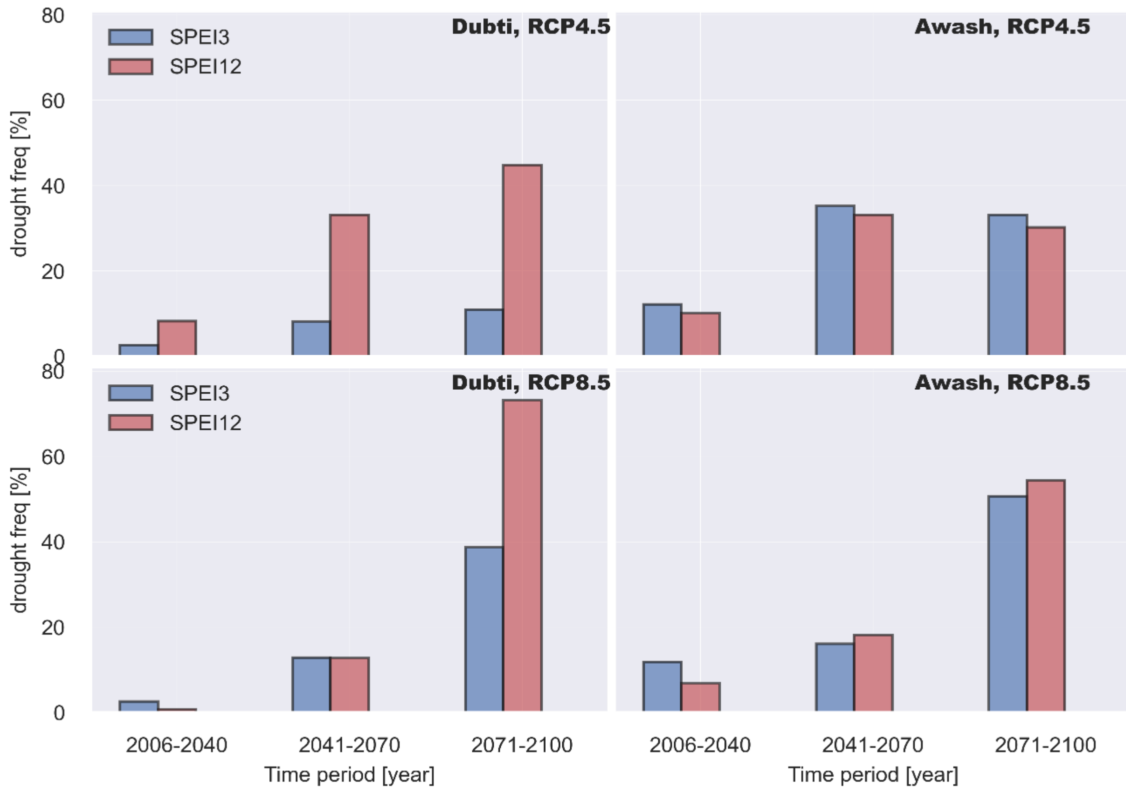

Figure 7| Drought frequency [%] at Dubti and Awash stations under RCP 4.5 and 8.5 climate scenarios for the near-term (2006-2040), mid-term (2041-2070), and end of the century (2071-2100).

As compared to the baseline climatological period (1981-2005), the average change in drought magnitude at Dubti station under RCP4.5 scenarios is likely to increase by 3.3% and 16.4% (near-century, 11.9% and 81.0% (mid-century), and 16.9% and 124.1% (end-century). Similarly, the average change in drought magnitude at Awash station is likely to increase by 14.0% and 11.4% (near-century), 43.5% and 46.1% (mid-century), and 36.8% and 39.2% (end-century). Under RCP8.5 scenarios, the average change in drought magnitude is likely to increase by 3.1% and 2% (near future), 17.1% and 41.0% (mid-century), and 68.4% and 252.2% (end of the century) at Dubti station. Likewise, the average change in drought magnitude at Awash station is likely to increase by 16.3% and 8.8% (near future), 22.8% and 25.6% (mid-century), and 74.0% and 93.6% (end-century) (Figure 8).

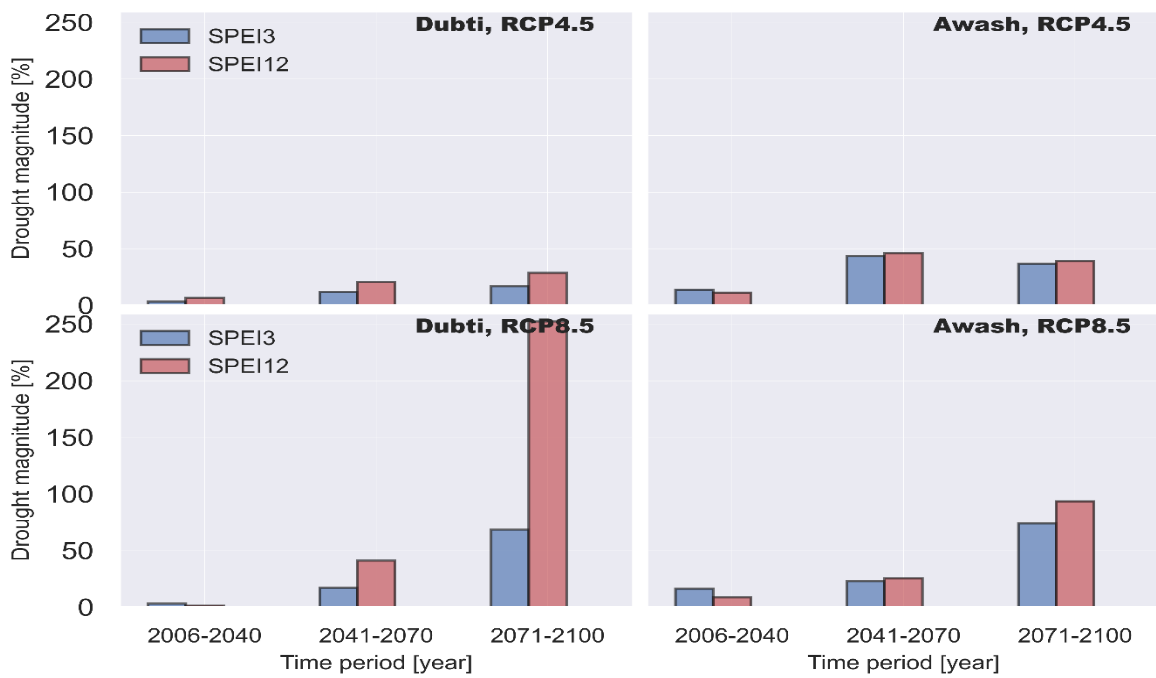

Figure 8| Drought magnitude [%] at Dubti and Awash stations under RCP 4.5 and 8.5 climate scenarios for the near-term (2006-2040), mid-term (2041-2070), and end of the century (2071-2100).

3.5 Association between drought and crop yield

The annual average productivity of major cereal crops (in quintal per hectare - qt/ha) over the entire Afar region for meher harvesting season was compared to the drought indices calculated by SPI and SPEI at 4-month time scale (June-September) period to evaluate the impact of drought on yield (Figure 9). We selected the medium time scale (4 months) to calculate drought as this time scale is suitable for describing agricultural droughts based on soil moisture availability, which provides a seasonal moisture estimation (WMO, 1987). The findings indicate that, in general, there is a significant increasing trend in crop yield over the region during the period 1994 to 2012 (Figure 9a). The correlation between drought indices and yield anomaly showed a strong positive correlation between calculated drought indices and yield anomaly (r^2 = 0.56 and 0.18 for SPI and SPEI, respectively (Figure 9b,c). Other non-climatic factors, such as improved seed varieties, crop management options, etc., are not considered in our analysis yet explain year-to-year yield variabilities.

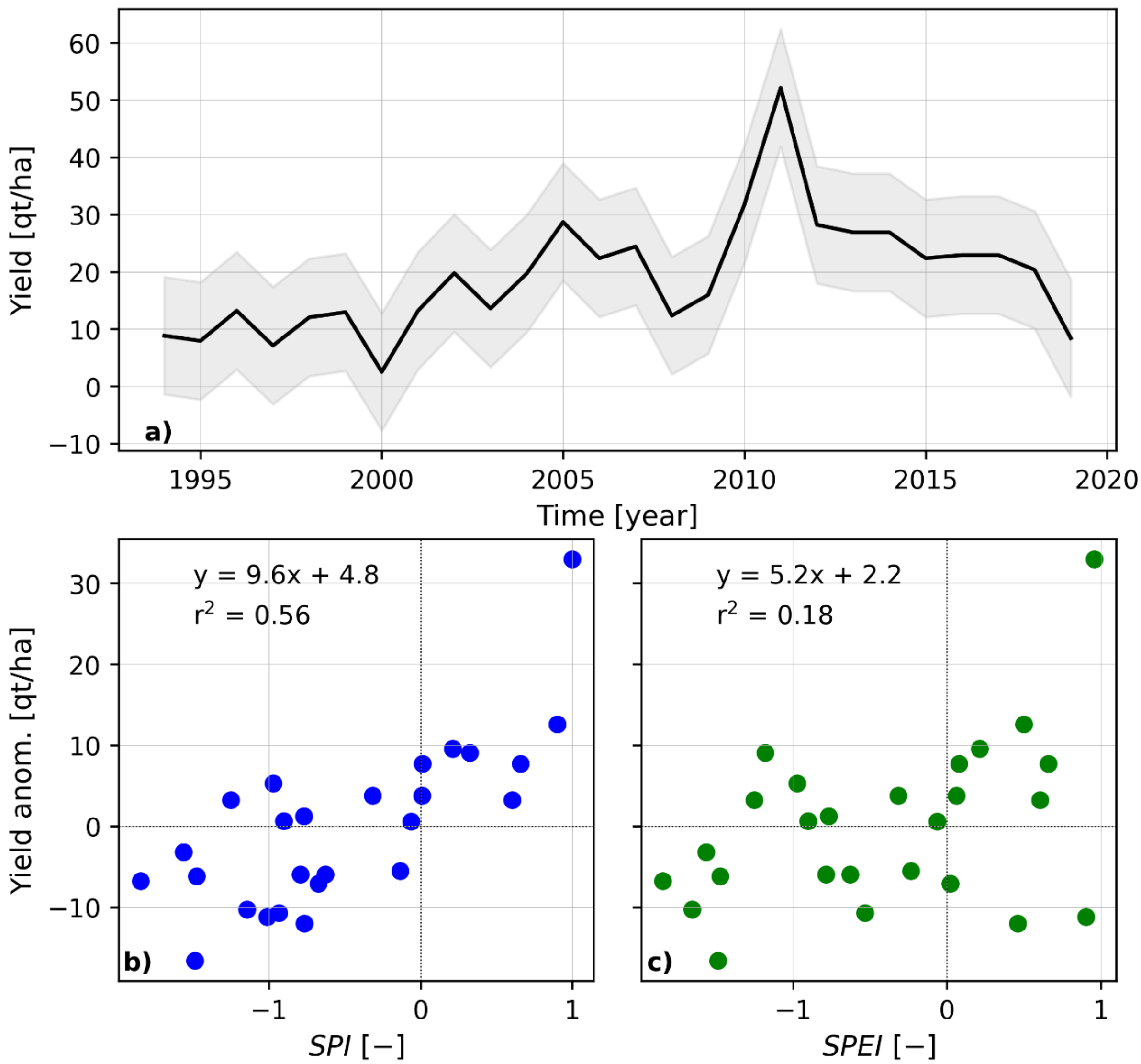

Figure 9| Observed average crop yield during Kiremt cropping season over 1994 -2019 (a), yield anomalies as a function of drought indices: SPI (b) and SPEI (C).

4 DISCUSSION

Ethiopia is a sub-Saharan African country located in the Horn of Africa. It is mainly vulnerable to drought, yet some parts of the nation are more vulnerable than others. Studies show that Ethiopia has experienced drought every two to three years, particularly in the northern and northeastern regions of the country (Mera, 2018). As reported by WFP, the 2015 drought was the worst in the past 30 years, exacerbating food insecurity in the nation (WFP, 2016). The Afar regional state is among Ethiopia's drought-prone areas, frequently and severely affected by recent drought. Recently, the region was severely affected by drought in 2005, 2009, and 2015, in which livelihoods were adversely affected (Ashenif, 2016).

Several researchers in Ethiopia have conducted meteorological drought studies, mainly examining historical data. Very few studies have highlighted future drought evolutions considering the ongoing climate change. The studies also considered Ethiopia, while limited ones focused on the Afar regional state. Furthermore, most of these studies evaluated drought using SPI, and only a few studies implemented SPEI based on satellite rainfall and temperature estimates. For instance, Viste et al. (2013) examined meteorological drought in Ethiopia using SPI from 1970 to 2011 and using data from the Global Precipitation Climatology Project. According to their study, on a national level, 2009 was identified as the second driest year, following 1984. In the 1984 drought over the Afar region, all districts were affected by the failure of seasonal rain (received only 18% of its expected mean annual precipitation) (Viste et al., 2013). Ashenif (2016) examined drought over the Afar region using SPI. The results showed extreme drought in the region in 2005, 2009, 2011, and 2015. In our study, we used >70% of the available climatic stations in the Afar region and deployed downscaled ERA5 reanalysis to fill the gaps in the observations. In addition to the SPI, we evaluated SPEI to consider the region's ongoing global warming and drought. The calculated drought indices are also associated with crop yield to understand the impact on the agricultural sector.

The temporal assessment of meteorological drought revealed that severe and extreme drought prevailed during the last 40-year period (1981-2020). The drought characteristics of both SPI and SPEI were consistent at different time scales. They well captured the historically known droughts during the last 40 years, particularly the more severe and extreme ones during the last 20 years. For example, the years 1984, 2008, 2009, and 2015 were considered to be the driest years across nearly all locations with varying levels of severity (Viste et al., 2013; Eze et al., 2022). Drought occurrences before 1970 were at least once every ten years; they have become more frequent and recently occurred every two or three years with varying severity (Gebrehiwot et al., 2011).

The spatial pattern of drought events at the 3-month time scale during the 1981-2020 period across the study area showed frequent drought prevailed with varying severity. The most severe and recurrent drought was recorded in Afar's southern and southwestern parts, particularly in the Gewane and Awash clusters under a medium-range time scale and in a few areas at the Dubti cluster, respectively. Under a longer time-scale, the most intense and frequent drought was recorded at the Dubti cluster (Figure 5a-f).

Our analysis shows that drought frequency and magnitude will likely increase. For representative stations, drought frequency is projected to increase in the near term (~10%), mid-century (~20%), and end of the century (>40%) (Figure 7). Similarly, drought magnitudes will also increase in the future compared to the present due to the ongoing climate forcing – increased temperatures and increased drying (Aiguo et al., 2004) (Figure 8). Studies have reported that increased global mean temperatures (Trenberth, 2005) may trigger more evapotranspiration and, thus, surface drying, thereby increasing drought intensity (Orke & Li, 2022).

There is a difference in the variance explained in yield by SPI and SPEI. This is resulted, for example, while the SPEI defined more drought as severe and moderate drought with long duration and increasing intensity, SPI determined more extreme drought than those detected by SPEI. Our findings show that crop yield losses (~3-17 qt/ha compared to the mean yield) in 1994-1995, 1999-2000, 2008-2009, and 2019 coincided with severe droughts. Overall, crop yield is strongly associated with calculated drought indices (r^2 of 0.56 for SPI and 0.18 for SPEI) (Figure 9). Moreover, it is noted that Ethiopian agriculture is mainly (>95%) rain-fed agricultural system (Minda et al., 2018). For example, a catastrophic crop loss was observed during the 2015 drought in the Tigray region (Eze et al., 2022). Reduced rainfall and increased evapotranspiration enhance drought occurrence, reducing soil moisture and the consequence impact of crop failures during the crop growing period. Alternative measures such as rainwater harvesting, supplementary irrigation practices, and drought-resistant crop varieties can be suggested to mitigate the recurrent drought impacts in the agricultural sector in the pastoralist region. Drought monitoring and early warning systems can be established and applied (WMO, 2006).

5 CONCLUSIONS

This study examined meteorological drought affecting agricultural productivity in the Afar region, northeast Ethiopia. It is mainly a pastoralist region and is among the frequently drought-affected areas in the country. Therefore, we evaluated the occurrence of meteorological drought using the present and future climate datasets. We also examined the relationship between drought and crop yield. To this end, we deployed 44 surface climatic stations in the Afar regional state to obtain daily precipitation and minimum and maximum temperature data. This data is evaluated for quality, and the missing records are filled out from the CHRIP dataset. To project the future drought, we used regionally downscaled models of the CMIP5 product. The data is corrected for biases. We systematically clustered the study area into four homogenous precipitations and calculated the standardized precipitation and evapotranspiration meteorological drought indices for temporal and spatial drought evaluation. The regional average cereal yield dataset correlates the drought estimates calculated by the indices to evaluate drought impact.

Therefore, our first research question was formulated as to how the spatiotemporal variation of drought has been characterized during the last 40 years. Our result shows a frequent occurrence of drought with varying degrees of severity. The years 1984, 2008, 2009, and 2015 are the driest years across all the meteorological stations. The most frequent drought was exhibited in the region's central, western, and southern parts, while the most intense drought prevailed over the Agroba cluster. Our second research question was related to quantifying the expected changes in drought magnitude and frequency in the coming decade compared to the base period. Our findings show that the average change in projected drought indicates more frequent and intense droughts will likely increase in the middle and end of the century than in the reference period. Our third research question was to analyze the association between meteorological drought and rain-fed cereal crop productivity. In this regard, our findings show that the annual yield variation explained 56% and 18% for the Meher (Kirment) harvesting season quantified jointly in the variation of SPI and SPEI, respectively.

Data and code availability

CHRIP data is available at https://data.chc.ucsb.edu/products/CHIRP/daily/netcdf/. AgERA5 data is available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agrometeorological-indicators?tab=overview. CMIP5 datasets: https://cordex.org/data-access/. CDT is an open source and can be accessed here: https://github.com/rijaf-iri/CDT. Python codes developed to analyze the data are available upon request.

Authors' contributions

T.B, A.K, T.T.M designed the study; T.B, T.T.M analyzed data and drafted the manuscript; T.T.M, A.K commented and edited the manuscript and supervised the study. All the authors read and approved the final version.

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Hydraulic Performance Analysis of Existing and Revised Water Supply Distribution Network, a case of Dukem Town in Ethiopia

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ABSTRACT

Analysing the status of a town's water distribution network is necessary to monitor its current and future management patterns. Dukem Town's existing water distribution system is not properly functioning; as the result, the utility is unable to deliver the required demand to customers. Thus, the main goal of this study was to analyse the town's water distribution system's hydraulic performance and the users' perceptions. Sample size of 376 households was used to assess the level of consumer satisfaction with the utility water delivery services. WaterGEMS software was used for the hydraulic performance analysis and the model was calibrated using eight nodal data points at minimum and peak hour consumptions, with corresponding R^2 of 0.97 and 0.99, respectively. The result of the analysis at steady state simulation indicated that 45.11% of the nodes had pressure above the desired limit, at average daily demand. At peak hour demand, the nodes with pressure within the desired limit reduced from 50% average demand to 34.3%. The analysis of pipe velocity showed that only 45.71 and 48.57% of pipes had a desired limit of velocity (0.5-2 m/s) at average daily and peak hour demands, respectively. The extended-period simulation showed only 45.36% of the nodes to have pressure within the desired limit. Moreover, 62.86% of pipes had less than the allowable velocity limit for the extended period. By applying pressure reducing valves, it was possible to keep 99% of the nodal pressures within the desired range. Even though there are recurrent water supply interruptions, the customers' satisfaction with the existing service is 55.4%. Generally, by integrating the findings from the hydraulic performance analysis and customer satisfaction assessment, decision-makers can make informed choices regarding infrastructure investments, operational strategies, and policy interventions.

Key Words: Customers Perceptions, Dukem Town, Hydraulic performance, *WaterGEMS,* Distribution Networks

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1. INTRODUCTION

One of the critical factors in ensuring public safety and the smooth normal urban activities is the efficiency of water distribution systems (WDSs) (Ataoui & Ermini, 2015). A water distribution system (WDS) is created and maintained in order to deliver a dependable water supply, that is, to adequately meet water user demands, especially under crucial operational conditions such as periods of peak demand (Vicente et al., 2016). Consequently, an essential requirement in the framework of WDS reliability is the study of the influence of water demand parameters (Zhan *et al*., 2020).

In developing countries like Ethiopia, most water distribution networks (WDNs) cannot fulfil their aim of providing sufficient water due to the frequent failure of their elements associated with poor design, construction, operation, and maintenance (Workneh et al., 2023). Generally, the focus of urban water management is to build infrastructure, with prime attention of augmentation; however, the distribution network hydraulics are usually ignored, and this does not lead to sustainable services (Jaiswal et al., 2021). An assessment of the hydraulic performance of a WDN could show if the system can provide consumers with the necessary amount of water at all times and locations (Shah, 2021). WaterGEMS is one of the preferred hydraulic modelling programmes used for the analysis and design of water distribution networks (Mehta et al., 2017). Its robust design method enables it to meet the standards for accuracy in the design of water distribution networks, control of distribution network variables including flow, pressure, and velocity, as well as their optimisation (Ostfeld et al., 2013). It is far superior to other WDN model software, especially EPANET, because to its integration with several platforms graphic applications (GIS tools, AutoCAD, and Micro Station tools).

On the other hand, customer satisfaction level is strongly linked to the four fundamental components of water service: quality, quantity, continuity, and price. Therefore, to ensure that water is delivered at a safely managed service level, rigorous assessments of piped water service providers should be conducted (Ajeng et al., 2018). However, according to Beker & Kansal (2023), more than 55% of urban Ethiopians have no access to water from safely managed services, and this is lower than the average for Sub- Sahara African countries and the world by 9% and 41%, respectively.

Dukem Town's water distribution system sometimes fails due to poor hydraulic performance of the distribution elements and in some places, there are prolonged disruptions of drinking water for unknown reasons. The town also does not have appropriate wastewater disposal systems, and if the leaking pipes are not promptly maintained, pollution may make its way into the network system (Mohammed et al., 2013). Consequently, it is important to use hydraulic computational tools, which are effectively combined with GIS tools, to assess and then improve the efficiency of the water distribution system (Tabesh et al., 2010). Thus, this study focused on hydraulic performance analysis of existing and optimized water distribution network of the town by using WaterGEMS software and assessment of costumers' satisfaction to existing water supply service. The study was limited to hydraulic performance analysis in terms of pressure, flow, and velocity within the existing water supply system. For the customer perception only the issues which are relevant to the topic and could be meaningful for good decision-making were considered. Thus, to address the main concerns always raised with water distribution systems in developing countries, daily water availability (per capita demand), distance travelled, water quality, adequate pressure in the system, and overall customer satisfaction with the existing system were considered the core issues. In this research, by carrying out a hydraulic performance analysis, the improvement and optimisation the current infrastructure of Dukem Town utility to deliver adequate water to the community, with sufficient pressure and velocity, was studied.

2. MATERIALS AND METHOD

2.1 Description of the Study Area

Dukem town is located 37 km South-East of Addis Ababa along the Adama-Dire Dawa-Djibouti transport axis. Geographically, the study area is located between latitudes of 8^o 45' 25" N and 8^o 50' 30" N and longitudes of 38^o 51' 55" E and 38^o 56' 5" E, covering a total area of 35.96 km^2 (Figure 1). It is located at an average altitude of 2100 m above sea level. The total population of the town was about 121,240 and the coverage of potable water was 65.7%, in 2020. The town's average annual temperature is 15.6 °C.

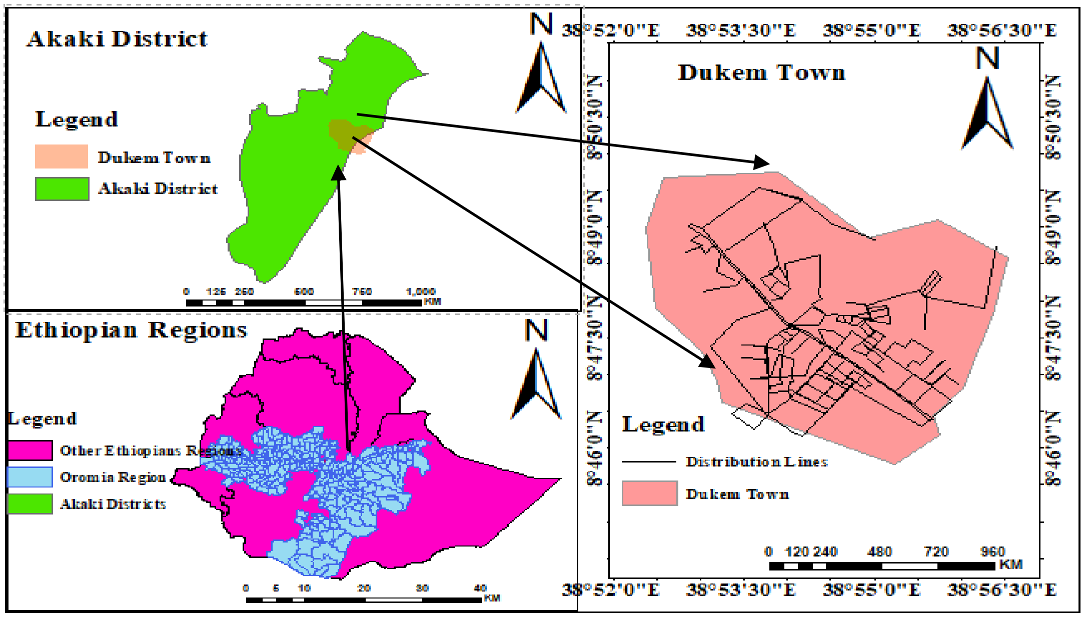


Figure 1: Location map of the study area

2.2 Existing Water Supply Condition of the Town

The water supply system of Dukem Town is fed by groundwater and has source from nine well field areas of deep boreholes. Currently, the total production of clean water in the town is 61.8 L/s. The average water supply of the utility for the 2020 year was 5,330 m^3/d. This average water production of the town was used to evaluate the performance of the existing distribution system based on the estimated water demand within the required water patterns. The average water demand was projected at 7,458.83 m^3/d in 2023 and the population number was 152,103. Thus, the average per capita consumption was 49.8 l/d. However, according to Ministry of Water Resource and Irrigation to GTP-II, the per capita consumption standard set for category-one towns, such as Dukem Town, was 100 l/d (MoWIE, 2022). Data recorded by the utility was used to estimate the water loss of the town and the result showed that, annual water loss of the town decreased somewhat from 2014–2018 (36 - 17%) and increased back to 30% in 2021. The water utility has not yet technically and for sure identified the main causes of water loss in the system.

The utility has five storage tanks, which are used to equalise flow to each service area. The municipality uses these storage tanks as a pressure zone boundary based on the topography to manage the distribution network. However, the geographical conditions and reservoirs location as well as the performance of water distribution network indicated that the main reason for water loss in this town is high pressure of water in some areas. Comparing the total water billed against the total production, the average water loss of Dukem Town water supply system was 39.5 %, which is well above the World Bank's expected maximum of 25 % and that is common in Ethiopian cities (Beker & Kansal, 2023). The network has 133 junctions, 176 pipes, 7 reservoirs, and 3 pumps, which were used in the analysis of the of Dukem town water supply system. The pipe materials of the network are HDPE, DI, UPVC and GS with internal diameter of 20-200 mm.

2.3 Data Collection Methods and Materials Used

Primary data was collected through observations and measuring nodal junction pressure for the calibration purpose in March and April 2023. From the field survey, x and y coordinates of nodes, tanks, and boreholes were collected. The data collected was transferred to WaterGEMS and simulated at Extended Period to compare the simulated result with the observed data. On the other hand, secondary data were collected from Dukem Town's water supply and sewerage service. Thus, population data, water demand, water consumption, water production, water loss, and borehole history data like depth, static water level, dynamic water level, discharge, pump head, and pumping hours, as well as existing pipe materials, junction, pump, and tank data, were all collected from the office. The equipment and materials used for the data collection were a pressure gauge to measure pressure at the selected nodes and GPS to collect the required elevation data during the pressure reading as well as to identify the exact location of the sample points. Google Earth for pre- and post-processing was used to collect, organise, and analyse the data. ArcMap v10.7.1 was used to display the overlapped shape file of the distribution network on the topographic map of the town and also for delineation of the study area. Global Mapper v20 was used to check the elevation of the junction, storage tank, water source, and coordinates of each node. IBM SPPS v21 and MS Excel were used to analyse the customers’ responses.

2.4 Data Preparation and Analysis Methods

The baseline for the overall performance assessment of the water supply system depends on base demand. To project future demand, the geometric increase method was employed to estimate the future population from 2023–2030. The data for the existing water distribution network of the town was generated in QGIS and Excel. Since the data from QGIS was lacking visuals, Google Earth Pro was used to relocate the distribution network, and all data relocated were added to Global Mapper v2022 to generate X and Y coordinates of junctions and reservoirs. The coordinates for each point were generated in Global Mapper v20 and then exported to Microsoft Excel 2013. Then data exported to Excel was transferred to WaterGEMS 10.2.3 software through the model builder toolbar to prepare setup for the network. The processed data in WaterGEMS was assessed and upgraded, then transferred to ArcGIS for further mapping of the network.

The existing demand data can be assigned to the network nodes in WaterGEMS software by point load data, area load data, or population (land use) data. In this study, to assign demand to distribution network, point data method, which is unit line option and the best to assign demand data to model especially in developing countries, was used. The unit line flow method divides the total demand in the system (or in a section of the system) into two parts: known demand (metered) and unknown demand (leakage and unmeasured user demand) (Momenzadeh et al., 2018). Dukem Town's utility records total water demand and not the demand of each junction, rather than locating the position of junctions. So, the base water demand of the town, which is 5338 m^3/d, was brought into the model by using WaterGEMS to load the building bar using the point data method. The demand scenario for peak hours was used for modelling, and demand was calculated for each supply node using the demand multiplier factors for a 24-hour flow period.

2.4.1 Population forecasting

According to the town's administration, the total population of the town was 121,240 in 2020 and projected up to 2030. The appropriate method for forecasting Dukem Town's population was the geometric increase method (equation 1), which was selected by comparing it with the Ethiopian Central Statistical Authority forecasting method using percentage error.

$$Pn = Po(1+r)^n \quad \text{……} 1$$

where Po is base population, Pn is population at n decades or year, n = decade or year, r = rate (percent increase).

2.4.2 Demand projection

The projection of water demand was based on the estimated population for a defined year. According to the town water service office reports, there are three major modes of service for domestic water consumers: house connections (HC), yard connections (YC) shared, and public fountains (PF) or communal taps. Base per Capita Water Demand by Mode of Service was set within national standards (MoWR, 2006). Running the model under scenarios of peak hour demand and average daily demand for the current year allowed for an investigation of the present system's hydraulic performance.

2.4.3 Model calibration and Validation

Firstly, the nodes of the network used for calibration and validation were junctions, which were added. Then, during the initial run, the model was calibrated using the Darwin calibrator toolbar on WaterGEMS by modifying flow-related sensitive parameters, including the water demand and pipe roughness coefficient, until they fell within an acceptable range. Both the correlation coefficient and the scatter plot were used to verify the validity.

Thus, by using a portable pressure gauge to take readings at 2-10% of all junction nodes, from low pressures to high pressures, calibration was carried out in accordance with USEPA water distribution system calibration guideline. Pressure from eight sample nodes of junctions (J-7, J14, J-30, J-44, J-61, J-71, J-109, and J-113) was measured near the corresponding location using a pressure gauge to calibrate and validate the model. The calibration of the model was performed at peak hour consumption in the morning (6.30–8.00 AM) and minimum hour consumption in the afternoon (2.30–4.00 PM). The sensitive parameters (pipe roughness and nodal demand) were then mildly adjusted until the simulated results resembled actual or field results. The validation was done manually using the correlation coefficient equation (R^2), which is:

$$R^2 = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2} * \sqrt{\sum(Y-\bar{Y})^2}} \text{---} 2$$

where: R^2 is coefficient of determination, X and Y are the computed and observed pressure values, and $\bar{X}$ and $\bar{Y}$ are mean value of computed and observed pressure, respectively.

2.4.4 Customer satisfaction assessment

Interviews were carried out by using sufficient sample size to represent the population to answer the questions about per capita water consumption, frequency of water supply, accessibility to water sources, and overall satisfaction with the existing water supply system. Thus, for the customer satisfaction assessment, the sample size (n) was determined using Yamane (1967) equation, which is:

$$n = \frac{N}{(1+Ne^2)} \quad \text{--} 3$$

where N is the total number of households (21,595) and e is level of precision (5% is taken).

3. RESULTS AND DISCUSSIONS

3.1 Hydraulic Performance Analysis of Town Distribution System

3.1.1 Model Calibration and Validation

The calculated values are within an average error at peak demand of 2.36 m and at minimum demand of 1.06 m of pressure simulated and observed values. As a result, the model's calibration was acceptable since it has met the calibration and validation standards for establishing pressure calibration and validation (average error 1.5 m to maximum 5 m). According to AWWA (2012), the liner regression relationship of pressure, which showed a typical difference error of between ±1.5m and ±5m, is considered an acceptable level of model performance. The observed values at minimum hour demand and peak hour demand are shown in Figure 2 respectively.

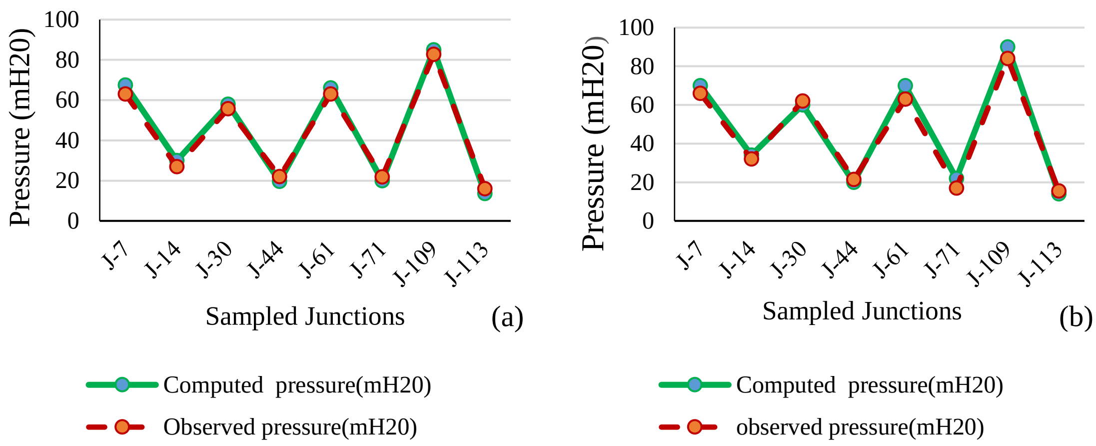


Figure 2: Computed and observed pressures at (a) minimum and (b) peak hour consumptions

On the other hand, the statistical correlation between the measured and simulated pressure during calibration for peak hour demand and minimum demand recorded R^2 of 0.98 and 0.97, respectively. R^2 of greater than 0.50 is considered acceptable for model performance (AWWA, 2012), and the result indicated existence of strong relationship between computed and observed values. The summarised validations at minimum and peak hour consumptions are shown in Figure 3.

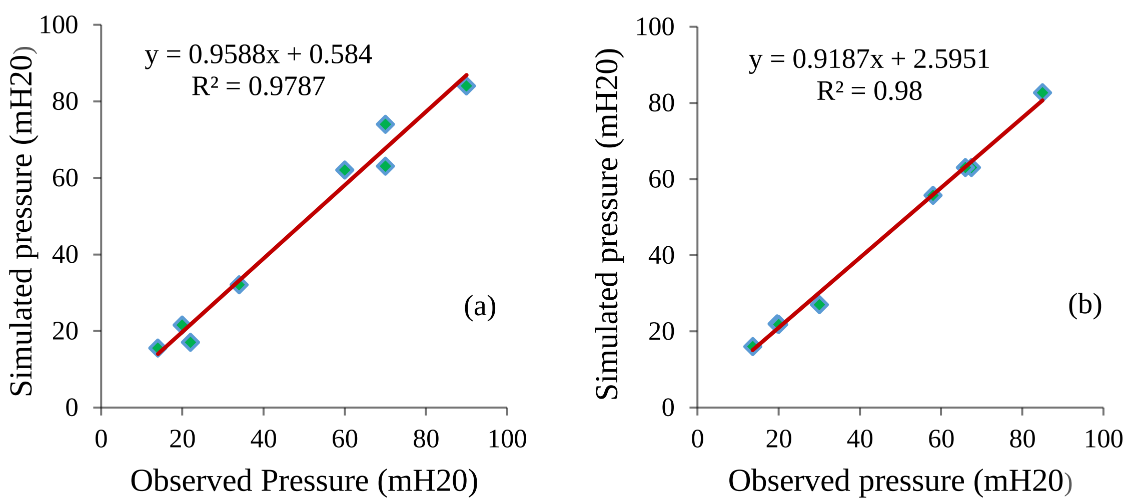
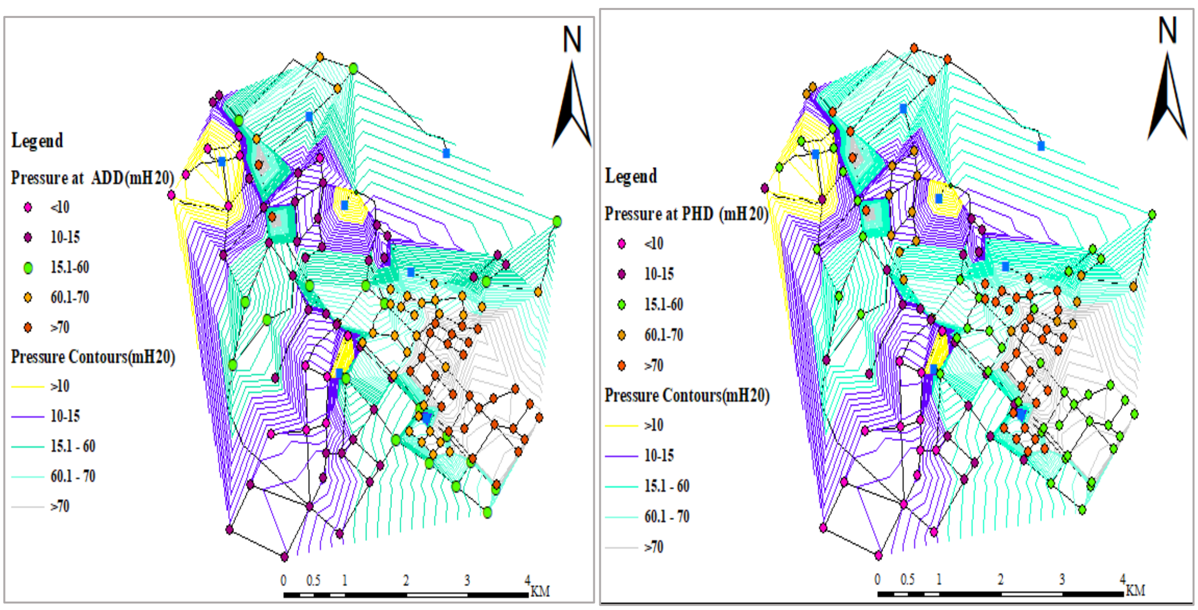


Figure 3: Validation at (a) minimum hour and (b) peak hour consumptions

3.1.2 Pressure and Velocity Analysis in Steady State Simulation

The pressures at average daily demand showed that 45.11% of the junctions had excess pressure (>70 mH20), especially at J61, J85, and J94-J111, which have significantly high pressure due to elevation of the reservoirs compared to the distribution area, as well as J125, J126, J217, J128, and A129, which have excess pressure due to lower elevations to the distribution line. In total, 50.38% of the junctions had pressure within the recommended limit, including acceptable in special conditions (10 to 70 m), and only 4.51% had undesirable pressure (<15 mH20). According to the national standard, the operating pressure in the distribution network should be (15–60 m) under normal conditions and (10–70 m) under exceptional conditions, and water velocity should be between 0.6 and 2 m/s, although one can find pipelines with zero velocity in the looped system (MoWR, 2006). The analysed values of junction pressures at average daily demand are shown in Figure 4.

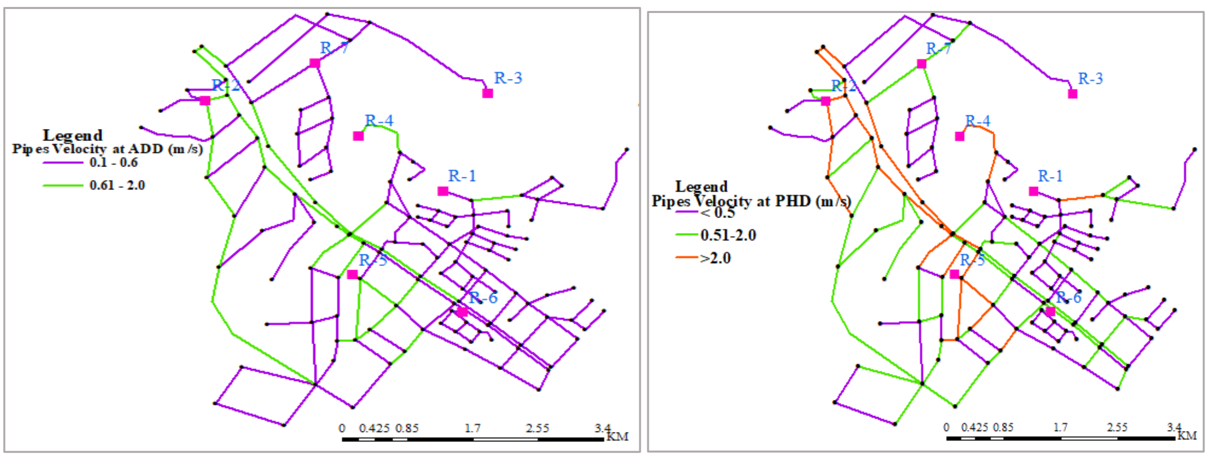


(a) (b)

Figure 4: Nodal pressure of the existing distribution system (a) at average daily demand and (b) at peak hour demand

The scenario of pressures at peak hour demand indicated that only 20.81% of the junctions had pressure >70 m H20, and 34.3% of junctions had pressure within the recommended limit (10 to 70m). 44.89% of the nodes have less than the allowable limit (15 mH20). The detail map of pressure at peak hour demand is indicated in Figure 4.

At average daily demand, no pipe had above allowable limit of velocity, 45.71% of the pipes were within acceptable velocity limit (0.5 - 2.0 m/s) and 54.29% of them were under acceptable limit (< 0.50 m/s) of velocity. This indicates that pipe velocity was very low at minimum hour consumption since there is high pressure in the system (Figure 5. But at peak hour demand (Figure 5), 8.57 % of pipes had above allowable limit (>2m/s), 48.57% had velocity within acceptable limit (0.5 - 2.0 m/s) and 42.86 % pipes were under acceptable limit of velocity (<0.5 m/s).



(a) (b)

Figure 5: Pipe flow velocity of the existing distribution system (a) at average daily demand (ADD) and (b) at peak hour demand (PHD)

3.1.3 Pressure and Velocity Analysis in Extended Period Simulation

For every hour over a 24-hour period, the model was simulated, where pressure and flow velocity changed in the system in response to variable demand. Demand patterns were used to simulate this fluctuation in demand over time. Demand patterns are temporally variable multipliers added to a base demand, most typically the average daily demand (Bentley, 2014). Therefore, average daily demand was used for pressure and velocity analyses in the extended-period simulation of this work. Most junctions had high pressure as demand fluctuated over 24 hours. 51.88, 45.36 and 3.76% of junctions had above allowable limits, within allowable limits and below allowable limits of pressures, respectively, at average daily demand (Figure 6.

The pipe velocity was also analysed at extended period simulation through 24-hours with respect to average daily demand. As a result, 62.86% of the distribution system had a pipe flow velocity less than 0.5 m/s, 37.14% of the pipes had a velocity of 0.6 to 2 m/s, which is the optimum adopted velocity, and there was no pipe with a velocity greater than 2 m/s in the distribution system (Figure 6.

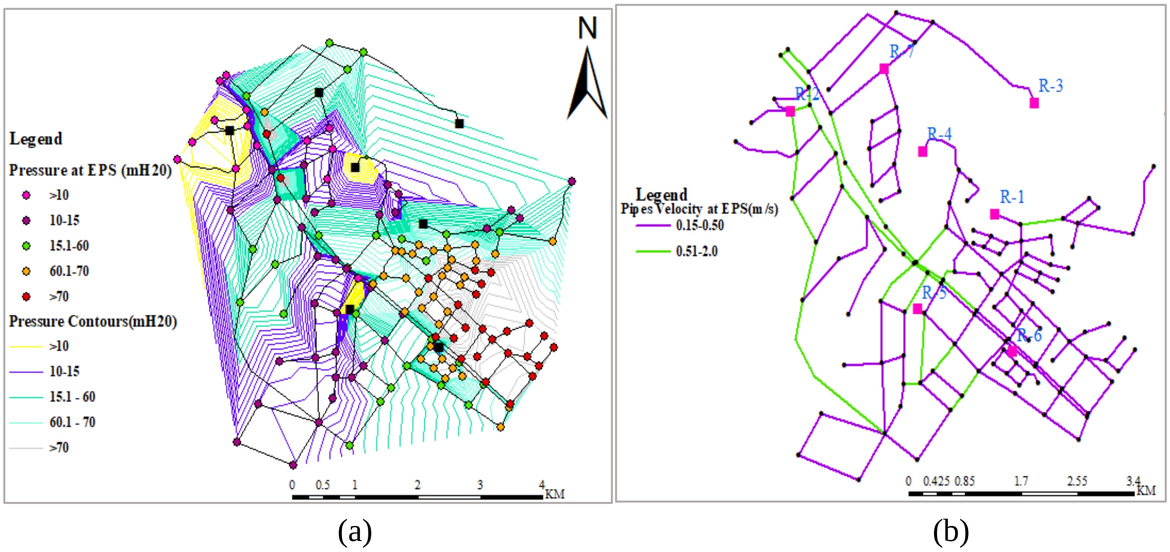


Figure 6: Extended period simulation maps the existing distribution system for (a) junctions pressure and (b) pipes velocity

Based on analysis performed in both steady-state and extended-period simulations, there were two identified major problems. The first main problem in the water distribution system of the town was that there were large number of nodes with pressure in excess of the permissible values due to the relatively high elevation of the reservoirs. Especially, during low consumption hours, the pressure level was significantly higher than the maximum allowable limit (>70 mH20). So, the high water loss in the system every year is understood to be caused by the excessive pressure in the distribution system. However, during high consumption hours, the water pressure was occasionally below the required level. The other main problem observed in the existing water supply system was that pipe velocity getting outside the recommended values. This means that when the pressure increased significantly, the pipe velocity become much below the minimum requirement of less than 0.5 m/s, to the extent of causing no flow conditions in some of the pipes. Therefore, to improve the observed problem, works related to adjusting the pressure to the allowable limit is required, say by applying additional elements to the system.

3.2 Optimization of the Existing Water Distribution Network

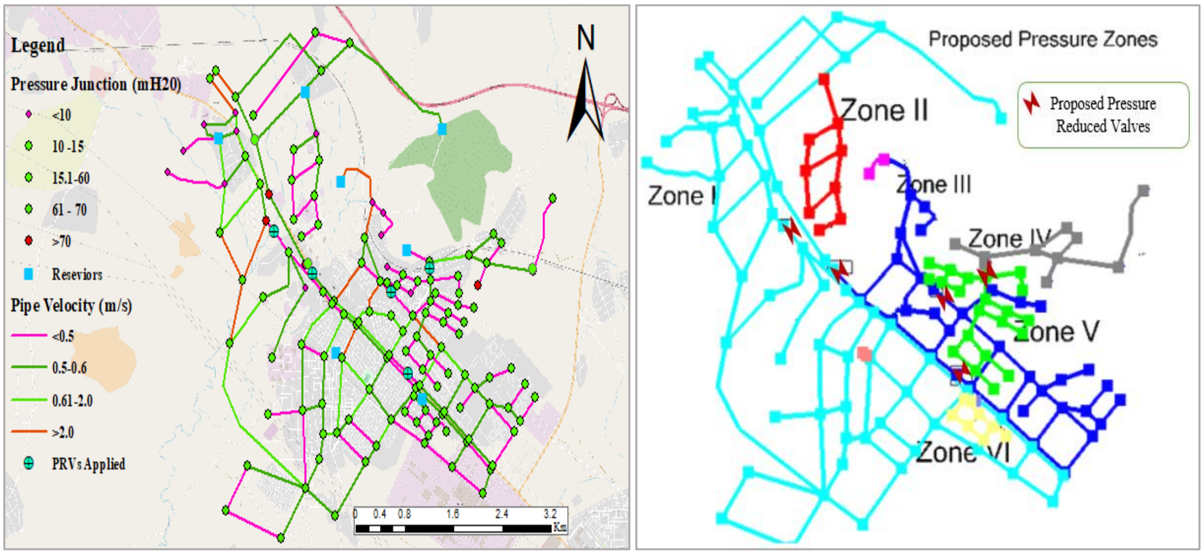
The distribution system can be adjusted to minimise the observed high pressure and to boost low pressure and velocity based on the results of model simulation. For this, a new pressure zone was created by applying pressure reducing valves (PRV) to decrease the high pressure observed in the system, and a pipe size arrangement was proposed to normalize pipe velocities and pressure to overcome the overall problem observed in the system. Even though there are several other options and techniques available to reduce pressure in a water distribution system, such as pressure-regulating pumps, flow control valves, changing pipe diameter, and demand-side management, the PRV was applied because the pressure from the elevated reservoirs is so high at lower elevations of the area, and the topography of the area does not allow for other options of pressure management. Thus, PRV were introduced as appropriate devices to control high pressure in this area. The pressures reducing valves were assigned to the system by considering high pressure observed (Table 1). Five PRV were introduced to pipes P-119, P-127, P-88(2), P-102(2), P-85(2), P-5 (2) and P-79 to decrease the high pressure observed in these areas.

Table 1: Location and description of the proposed pressure reducing valves

Label	Elevation (m)	Y (m)	X (m)	Valve Dia. (mm)	Pressure (mH_2O)	
					From	To
PRV-1	1,952.33	972,553.01	490,668.05	100.0	73	28
PRV-2	1,977.68	972,497.65	488,739.75	100.0	131	22
PRV-3	1,957.56	973,006.09	488,109.79	100.0	91	26
PRV-4	1,949.88	972,260.54	490,027.25	100.0	60	44
PRV-5	1,934.00	971,262.84	490,309.42	80.0	62	33

As pressure of junctions has been adjusted, velocity of pipes also improved and lower pressure junctions become within the standard pressure ranges. As a result, 95.36% of the nodes had pressure within the desired limit, whereas only 1.88 and 2.76% of nodes had pressure above and below the desired limit, respectively. Correspondingly, 37.14% of pipes had less than the allowable velocity limit, and 62.86% of them were within the desired limit. The modified junctions pressure and velocity of pipe are shown in Figure 7.

Allocating nodes to their proper pressure zoning gave the chance for the nodes to receive better flow and pressure head. Pressure zones were set up to regulate pressure in locations where large grade changes could create too much pressure at the lower end of the system and not enough pressure in the higher ends. The boundaries of the six pressure zones were suggested for Dukem Town's water supply system based on PRV placement and consideration of dispersed water sources in the town (Figure 7.



(a) (b)

Figure 7: (a) Modified pressure and velocity of the System and (b) pressure zones of the modified system

3.3 Customer Satisfaction Level with Existing Water Supply System

The sample size of 376 was randomly selected to investigate the level of customer satisfaction with the town's water supply services. Based on the demographic characteristics of the respondents, 63.9% of them were female. The main age groups were 31–40 and 41–50 years, making 39.1 and 25.9%, respectively, of the total sample size. More than half (54.3%) of the contacted consumers had an education level of at least a secondary school graduate. The income sources of the respondents were daily labour, business/trade, and farming, which are 26.6, 24.73, and 24.23%, respectively.

Figure 8 shows the number of households with and without access to adequate water to be 59.50, and 40.50 %, respectively. Two-third of respondents were satisfied with pressure in the pipe; specifically, those householders residing at lower areas of reservoir location were benefited as they always receive water of sufficient pressure. More customers of the town speak unfavourably of the cost of water. The mode of water service has shown that 35.6 and 34.1 % of the households use yard connection (YC), and public fountain (PF), respectively. But the proportion of households that use House Connection (HC) was only 24.1%. This shows that most households are currently using communal pipes and they need additional water supply to upgrade the system of piping inside their house.

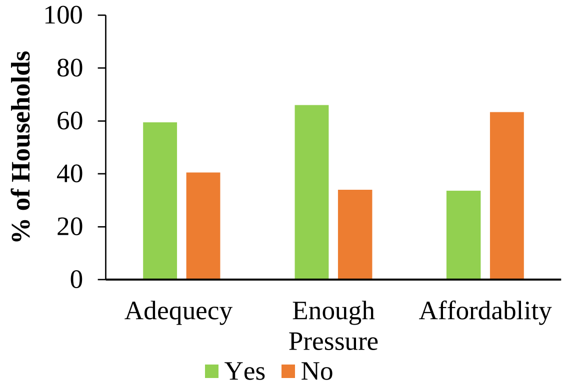
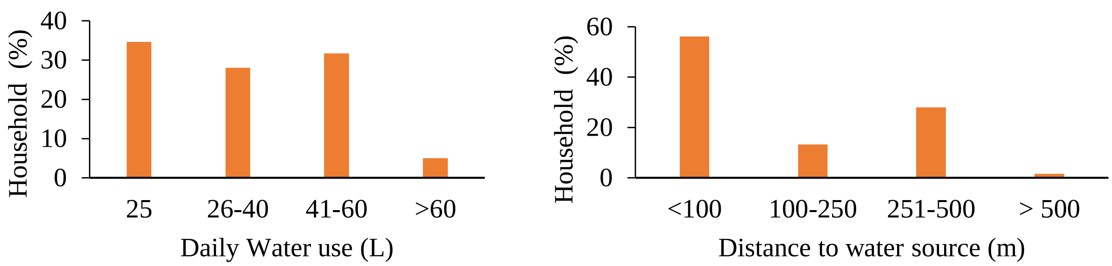


Figure 8: Customer responses to adequacy, pressure and affordability of water

With respect to the quantity of water collected from the source, only 5% of households get above 60 l/d (Figure 9 . Based on the average family size of 3 people, the average per capita water consumption of the town was 12.58 l/d, which is far below the World Health Organization criteria of at least 20 l/p/d for a basic household use. Regarding the accessibility of customers to water sources, more than half of the households (56.2%) have access to water at a distance of less than 100 m. Only 1.6% of households have to cover more than half a kilometre to fetch water (Figure 9 .

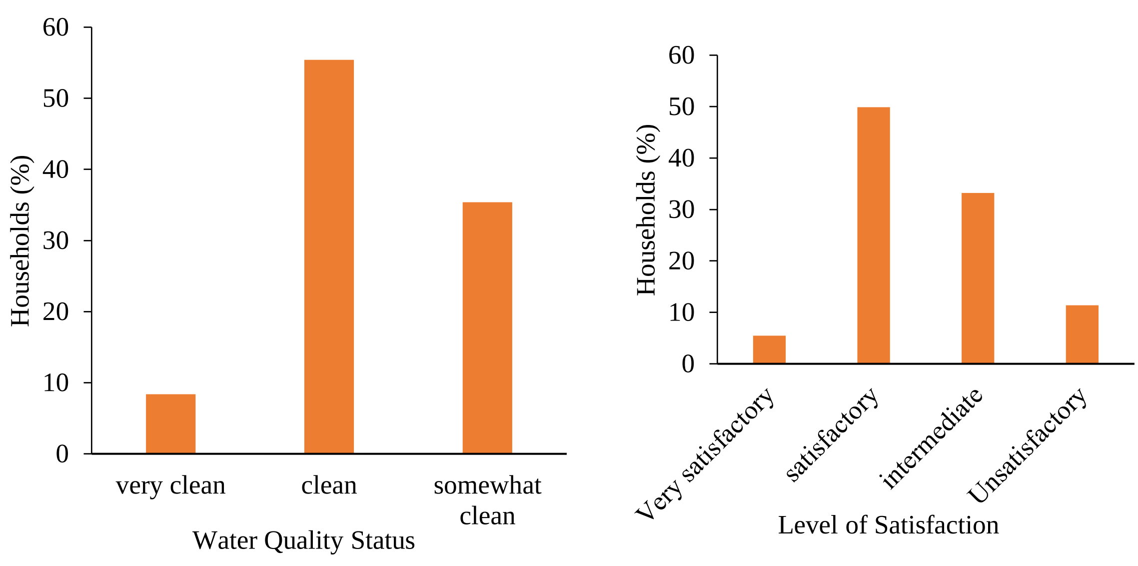


(a) (b)

Figure 9: Customer responses to (a) daily water consumption and (b) distance to water sources (m)

For improved supply with respect to distance travelled to fetch water, 29.6% of customers yet to be served according to the standards (maximum distance) set by Growth and Transformation Plan-II (MoWIE, 2022). According to the standard, urban population must have access to urban water supply with a GTP-II minimum service level of 100 l/c/day for category-one towns and cities at a distance of 250 m. However, 39.21% of the households walk more than 500 m to get water due to drought (winter), water scarcity, and nearby community pipes that are sometimes closed. Regarding the continuity of supply, 43.5% of households get water once a day, which stays for 1-3 hours, 41.7% gets water once in two days, which stays for 3-5 hours, and the others get it twice a week, which stays for more than 5 hours.

Related to the water quality status, most households are satisfied with the clean water from the sources (Figure 10. Overall, more than half of the population are satisfied with the water supply system and 11.4% of them were discontented (Figure 10 . According to Kassa et al. (2017), the overall satisfaction of a town with the existing water supply service should be at least in average 50%, which agree with this level of satisfaction with the existing water supply service of Dukem Town.



(a) (b)

Figure 10: Customer responses to the water quality and (b) the overall customers' satisfaction

4. CONCLUSIONS

The main objective of this study was to model the existing water distribution system in Dukem Town and then, based on the identified problems, to propose modifications. Moreover, the customer's perception of the existing system was assessed. The estimated current total average water demand is 5953.37 m^3/d, and the utility needs to provide additional sources that produce 2044.37 m^3/d to satisfy demand by 2030, which is projected to be 7997.74 m^3/d. Moreover, 51.88 and 3.76% of nodes had pressure above and below the desired limit, respectively. Correspondingly, 62.86% of pipes had less than the allowable velocity limit. The modifications to the existing water distribution system were proposed by creating pressure zones and by introducing pressure-reducing valves to manage the excess pressures. As a result, 95.36% of the nodes could have pressure within the desired limit, and 62.86% of the pipes had velocity within the desired limit. From the customer perception study, the average amount of water collected per household was 37.5 l/d. Most households have access to water at a distance of less than 250 m, and only 28 and 1.6% of households access water at 251–500 m and >500 m, respectively. However, the majority of the householders were dissatisfied with the affordability of water. Overall, even though the water supply system had shown low hydraulic performance, more than half (55.4%) of the customers were satisfied with the existing service. In order to minimise the high pressures and reduce water loss in the system, it is recommended to implement the proposed improvement. Moreover, the utility needs to gather customers’s perceptions of the water distribution system from time to time to know their attitudes and then to take necessary decisions. In addition, the resilience and sustainability of the water supply system should be examined by combining hydraulic performance analysis with risk assessment models, climate change projections, and infrastructure resilience planning. These steps will allow for a thorough assessment of the system's overall water losses as well as revenue and non-revenue water in the town.

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Hydro-communication Efforts of Ethiopia for Equitable and Reasonable Utilization of Nile River Basin (1902-2023)

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ABSTRACT

Many studies have addressed the issue of Nile River Basin from the perspective of international water laws, hydro-politics, cooperation benefits and water resource management, but less is known about hydro-communication efforts of Ethiopia for equitable and reasonable utilization of the river basin. This study, therefore, examined hydro-communication efforts Ethiopia exerted and contributing factors in order to ensure equitable and reasonable utilization of Nile River Basin. The study is important for revealing communication efforts of Ethiopia to utilizing the basin and for constructing body of knowledge to hydro-communication as field of study. The study employed constructivism research perspective and qualitative research approach. Various major and pertinent documents such as international conventions of universal application in general and agreements, press releases, aide-memoire, initiatives, media outlets and remarks on Nile River Basin in particular were used as data source. The study used qualitative content analysis along with historicism as data analysis technique. Two-level games theory was used as lens in doing the analysis. The findings revealed that hydro-communication efforts of Ethiopia have shown remarkable progress from being completely reactive from 1902 to 1990s to being influential since 1999. National level efforts and global realities have collectively been the major factors for the progress. However, Ethiopia has experienced unprecedented pressure from Egypt and its allies especially since 2011. Hence, hydro-communication efforts of Ethiopia should be upgraded to strategic communication level to withstand the pressure and fully ensure equitable and reasonable utilization of the basin.

Keywords: hydro-communication, equitable and reasonable utilization

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1. INTRODUCTION

Hydro-communication, in its general sense, refers to communication with regard to water resources. When it comes to transboundary river basin, hydro-communication refers to a dynamic interactive process of sharing facts, ideas, thoughts and values on a river basin with the purpose of realizing a given mission. The general mission of hydro-communication on transboundary river basin is to ensure sustainable management which includes ensuring equitable and reasonable utilization of a given basin (Rieu-Clarke, 2012) and meeting the needs of the present generation without compromising the ability of the next generations to meet their own needs from the basin (Camarinha-Matos et al., 2010). However, with no required attention given to hydro-communication, which is sine qua non for cooperation on transboundary river basins, cooperation for sustainable management of transboundary river basin which is complex, difficult and demanding (Atwan, 2018; Furlong, 2006; Yacob, 2007; Zeitoun & Warner, 2006) has become a much talked about issue.

Ensuring cooperation on Nile River Basin has been complex and problematic. Failure of the Nile Basin Initiative, which started in 1999, to reach basin-wide comprehensive agreement among riparian states and failure of the Washington Tripartite Negotiation to come to terms among Ethiopia, Sudan and Egypt are indicatives of this. Nile River flows through eleven riparian states such as Ethiopia, Eritrea, Burundi, Tanzania, the Democratic Republic of the Congo, Rwanda, Uganda, Kenya, South Sudan, Sudan and Egypt before it empties into the Mediterranean Sea (Nile Basin Initiative, 2018). However, the downstream states, most notably Egypt has been enjoying monopoly over it (Waterbury, 2002; Zeitoun & Warner, 2006).

Despite the long-standing hydro-hegemony of Egypt over the Nile, Ethiopia has never stopped seeking for equitable and reasonable utilization of the Nile. Ethiopia has been seeking this because Nile River Basin means a lot to it. For instance, Nile River Basin in Ethiopia is source of daily livelihood for around 37.6 million Ethiopians(Nile Basin Initiative, 2016). Besides, 58% of the hydro power development potential of the basin is located in Ethiopia(Waterbury, 2002) where more than 65% of the population has no access to electricity (Yihdego, 2020). Moreover, the basin covers 32 % of Ethiopia(Yacob, 2007), and 70 % of water resources of Ethiopia which is water stressed country is found in the basin (USAID, 2021). Furthermore, half of the total 3.7

million ha that can be developed for irrigation but only 5-6 percent has been developed in Ethiopia is found in the basin(Awulachew et al., 2009). Equally important, Ethiopia’s head waters provide 85% of the Nile water(Yacob, 2007) which implies that Ethiopia is by far the major source of Nile. As a result, Ethiopia has the right to utilize Nile River Basin on one hand, and it (Ethiopia) has no any other viable alternative except ensuring equitable and reasonable utilization of the basin on the other hand. Since ensuring equitable and reasonable utilization of Nile River Basin could bring about remarkable developments in Ethiopia, Nile River Basin is Ethiopia’s strategic transformative natural resource that determines the fate of sustainable development of Ethiopia.

Many studies have addressed the issue of Nile River Basin from the perspective of international water laws (Dereje, 2010, 2018), hydro-politics (Abrham, 2004; Yacob, 2007), cooperation benefits(Abrham, 2004; Cascão, 2009; Salman, 2013) and water resource management (FAO, 2011; Whittington et al., 2005), but less is known about hydro-communication efforts on the river basin. Hence, this study intended to assess hydro-communication efforts Ethiopia exerted to ensuring equitable and reasonable utilization of Nile River Basin, associated factors and role of hydro-communication efforts to ensuring sustainable management of the river basin. This is important for theoretical and practical reasons. First, this knowledge can help to construct body of knowledge of hydro-communication as field of study. Second, this knowledge can help Ethiopian experts and politicians taking part in negotiations and discussions over Nile River Basin to be aware of the long way Ethiopia has come and take intervention measures accordingly.

2. METHODOLOGY

Constructivism, which argues that knowledge and meaning is generated and constructed from interactions or communication with others and with experiences through time (Creswell, 2013; Mogashoa, 2014), is taken as a research perspective. Consistent with constructivism, this research is based on two arguments: first argument is that physical or natural reality transcends into social reality through communication (Berger & Luckmann, 1991; Hiebert, 2014). The second argument consistent to constructivism is that looking at the whole of a phenomenon and maintaining emphasis on processes is much more meaningful than singling out one variable causing the outcome with the aim to create order out of disorder(Keyton, 2018).

This research employs qualitative research approach. Secondary data was used as data source. Various major and pertinent documents such as international conventions of universal application in general and agreements, press releases, media outlets, aide-memoire, initiatives and remarks on Nile River Basin in particular were consulted. Qualitative content analysis, which is defined as any meaning creation effort from big qualitative documents(Patton, 2024) was employed as data analysis technique. Besides, in order to deal with progresses and associated factors as water is not a standalone issue(Furlong, 2006), the study adapted ‘historicism’. Historicism is considered in the sense that events are affected by historical changes happened at specific periods of time and places, and understanding them should be within their historical contexts (Reynolds, 1999). Hence, major global political realities and developments with regard to transboundary water resources at different times along with two-level games theory(Putnam, 2009) were used as lens to doing the analysis.

3. RESULTS AND DISCUSSION

3.1. Major Hydro-communication Instances and Efforts in 1902-2011

In a secular recorded history, hydro-communication effort of Ethiopia on Nile River Basin goes as far back as the 1902 when Emperor Menelik (1889-1913) tried to defend the river basin as national natural resource in the treaty between Great Britain (as colonial power of Sudan) and Ethiopia to regulate the frontier between Sudan and Ethiopia. The river basin was mentioned in Article III which reads as:

> *His Majesty, the Emperor Menelik II, King of Ethiopia, engages himself towards the Government of His Britannic Majesty not to construct or allow to be constructed, any work across the Blue Nile Lake Tana, or the Sobat which would arrest the flow of their waters into the Nile except in agreement with His Britannic Majesty’s Government of the Sudan* (Abrham, 2004, p. 64)

The Amharic version of this article reads as:

> *ጃንሆይ ዳግማዊ ምኒልክ ንጉሠ ነገሥት ዘኢትዮጵያ ከጥቁር ዓባይና ከባህረ ጣና ከሶባት ወንዝ ወደ ነጭ ዓባይ የሚወርደውን ውሃ ከእንግሊዝ መንግስት ጋር አስቀድሞ ሳይስማሙ ወንዝ ከዳር ዳር የሚደፍን ስራ እንዳይሰሩ ወይም ወንዝ የሚደፍን ስራ ለመስራት ለማንም ፈቃድ እንዳይሰጡ በዚህ ውል አድርገዋል(Hailu, 2013, p. 102)*

Although Egyptian scholars and politicians still mention this communication instance as binding and Ethiopia could not make use of the river basin without the consent of downstream states, it could not be valid on multiple grounds. First, the Amharic version of the Article reads as '...ወንዝ ተዳር እዳር የሚደፍን ስራ... or its literal translation is "*...shall not block the waters from bank to bank'* which Ethiopia has never done and is not doing". Second, any treaty signed before 1919 is not valid unless it is sent to and registered by the United Nations Head Quarter (Hailu, 2013). Third, Ethiopia repudiated the 1902 Treaty on account of British recognition of the Italian "conquest" of Ethiopia(Kendie, 1999). Hence, Ethiopia's hydro-communication on Nile River Basin made no concession to colonial powers.

Ethiopia wanted to construct a dam on Lake Tana's outlet to the main 'Abbay' River, the main source of Nile in Ethiopia, and to sell the water to the British Government in Sudan or to their cotton corporations there (Yacob, 2007). The study of this project was done with the support of the American J.G. White Engineering Corporation in 1929-1934. However, this move of Ethiopia failed as a result of the opposition Great Britain expressed to United States of America (Hailu, 2013). Moreover, it was during this period that Great Britain (on behalf of Sudan) and Egypt as independent state signed the 1929 bilateral agreement.

Following its independence in 1956, Sudan needed the revision of the 1929 agreement. To this end, Sudan and Egypt started negotiation excluding Ethiopia. Opposing this bilateral move, Ethiopia, as a reaction, wrote a circular aide-memoire to the diplomatic community in Cairo in September, 1957(Hailu, 2013). The excerpt of the aid-memoire reads as below.

> *...Just as in the case of other natural resources on its territories, Ethiopia has the right and obligations to exploit the water resources of the Empire…for the benefit of the present and future generations of its citizens... in anticipation of the growth in population and its expanding needs… (*Whiteman, 1964: 1011-13) cited in (Yacob, 2007, p. 100).

This circular aide-memoire was another major hydro-communication effort of Ethiopia. Then, it was at this period that hydro-communication of Ethiopia to defend national interest concerning Nile River Basin started to take institutional shape.

Either having been frustrated by Egypt and Sudan bilateral negotiation that excluded Ethiopia or having learned that utilizing the resource, as said in the aide-memoire, was the quest of the time, Ethiopia gave a lengthy statement concerning Abbay (Blue Nile) Master Plan Study in November 1957. Excerpt of the statement reads:

> *We have already explained that the plans are under construction to utilize our rivers as an essential step in the development of agriculture and industry… Ethiopia may be prepared to share this tremendous God given wealth of hers with friendly nations neighbouring upon her, for the life and welfare of their people…. (*Ethiopia Observer, Vol. II, No. 2, 1958: 93 cited in (Yacob, 2007, p. 101).

The sentence "*Ethiopia may be prepared to share this tremendous God given wealth of hers with friendly nations neighboring upon her, for the life and welfare of their people"* indicates how hydro-communication of Ethiopia on Nile River Basin was a move ahead of the time of the notion of equitable and reasonable use of transboundary river basins indicated in the 1966 Helsinki rule and in the 1997 UN Water Convention.

The Abbay (Blue Nile) Master Plan Study was launched aimed at accomplishing three missions: to provide a regulated water supply for a hydroelectric power station to be installed downstream on the Abbay River, to obtain a regulated supply of water for the planned irrigation schemes further downstream in the valley, and to use the results of the basin study as a modality of water sharing in an event of negotiation with downstream nations (Zewde, 2000: 9) cited in(Yacob, 2007). The Master Plan Study was knowledge production or working on information, which is one of the three elements along with institution and infrastructure, necessary for sustainable water management (CIWA, 2015). It could also be taken as the foundation for ideational power on the Nile River Basin.

It is not wrong to say that the aide- memoire, the statement concerning the Master Plan Study and the launching of the Master Plan made Egypt and Sudan anticipate the coming of a third party in the future and included how the third party should be treated in Article five of the 1959 agreement, though not applied yet. Article Five-General Provision-, number 2 reads:

> *As the riparian states, other than the two Republics, claim a share in the Nile waters, the two Republics have agreed that they shall jointly consider and reach one unified view regarding the said claims. And if the said consideration results in the acceptance of allotting an amount of the Nile water to one or the other of the said states, the accepted amount shall be deducted from the shares of the two Republics in equal parts, as calculated at Aswan*(United Nations-Treaty series, 1963).

Egypt constructed the Aswan High Dam which impounds above 160 billion cubic meter water with the financial support gained from Soviet Union in 1960-1970. However, Egypt blocked the loan Ethiopia could secure from Africa Development Bank for the translation of the Master Plan Study into practice in 1964 (Hailu, 2013).

At the back of the Helsinki Rules, Article 5 which reads as "*Each basin State is entitled, within its territory, to a reasonable and equitable share in the beneficial uses of the waters of an international drainage basin"*(International Water law project, 1967), Egypt initiated 'Hydromet' in 1967. 'Hydromet' was a hydro-communication platform to which Ethiopia became an observing member in 1971. The forum was no more than being containment to the participants and isolation to Ethiopia strategy of Egypt to establish its hydro-hegemony. It should be noted that the Camp David Accord signed between Egypt and Israel in 1978 accentuated that US and Egypt established a close alliance(Zeng et al., 1994) which gave Egypt privilege to receive military and economic assistances annually on one hand and become regional power on the other hand (Kameri-Mbote, 2007).

Then, another incomplete, hydro-communication forum called 'Undugu' ("brotherhood" in Swahili language) came into being in 1983. Although its aim was to create cooperation in such common fields such as culture, environment, telecommunication, electric power, trade, and water resource development, it was used utilitarian compliance-producing mechanisms to maintain hydro-hegemony. Ethiopia which chose to take observer status, however, challenged 'Undugu' as having no legal standing and no competence to submit a plan of action for the Nile Basin (van der Kley & Reijerkerk, 2009). Likewise, Ethiopia challenged and criticized the basin-wide study made to evaluate the state of affairs following the agreement of the Nile Basin Ministers in 1986 for the need for a basin-wide integrated development. Criticizing this report for being biased as it mainly addressed the needs of additional water supply for the downstream countries, Ethiopia developed a proposal 'Integrated Development of the Nile Basin' which got acceptance by the Nile Basin delegation except Egypt and Sudan. This indicated Ethiopia's strength of hydro-communication. It also showed cooperation of upper riparian states, but unfortunately, it didn't show progress afterwards (Dereje, 2010). The factors that contributed to the initiation of 'Hydromet' and 'Undugu' by Egypt were Cold War global realities such as war for perceptions or introduction of ‘soft’ power(Taylor, 2003), and, the increase of regional hegemony formation (Furlong, 2006)..

Technical Cooperation Committee for Promotion of the Development and Environment Protection of the Nile Basin, (TECCONILE) which was much better hydro-communication platform than its predecessors on Nile River Basin came in 1992 (Dereje, 2010). Immediately after it, the Framework for General Cooperation was signed between the Arab Republic of Egypt and Ethiopia in Cairo on 01 July 1993(Hailu, 2013). It was the first written consensual approach between the two states.

After four years of the Framework for General Cooperation agreement, the 1997 UN Water Course Convention known for principles of equitable and reasonable utilization which is constitutive and not causing significant harm which is interpretative put for vote. In the voting, 106 countries including Kenya and Sudan, 26 countries including Ethiopia, Egypt, Rwanda and Tanzania of the Nile Basin states, three countries (China, Turkey and Burundi), and 31 countries including Eritrea, Zaire (Congo) and Uganda of the Nile River Basin states were in favor, abstention, against and absentees respectively(Rieu-Clarke, 2012). Following the ratification of the convention by Viet Nam on 19 May 2014 as 35th country, the UN Water Course Convention was expected to enter into force in August 2014 after 90 days of the ratification (IISD, 2014). This was the biggest development in international water law so far.

Encouraged by this convention and the ideas and direction of debate obtained from the Nile Conferences which started in 1993 and staged every year on a rotation basis among the basin countries, nine of ten Nile Basin riparian states established the Nile Basin Initiative in 1999. Eritrea participated as an observer. Following its independence in 2011, the Republic of South Sudan has become the eleventh riparian state of the Nile River Basin. The motto of the Nile Basin Initiative is “Sustainable development of the river Nile for the benefit of all”; whereas, the shared vision of the Nile Basin Initiative is “To achieve sustainable socio-economic development through equitable utilization of, and benefit from, the common Nile Basin water resources”. The World Bank in collaboration with the Canadian International Development Agency (CIDA) and the United Nations Development Program sponsored the establishment of the Nile Basin Initiative. This was a very huge breakthrough hydro-communication for upper riparian states, most importantly for Ethiopia. This hydro-communication was application of empowered participation in which stakeholders participate in the process and joint analysis as equal partners (Mefalopulos, 2008).

The global environment changes such as relative weakening of bi-polar tension (East-West tension) resulted in the decrease of inter-state conflicts (end of proxy war) and, the treatment of water as economic good combined with decentralized management and full participation of stakeholders following the end of cold war in 1991(Furlong, 2006) were facilitating factors for the 1993 communication effort framed under 'Framework for General Cooperation between the Arab Republic of Egypt and Ethiopia' , the 1997 UN Water Course Convention, and the 1999 Nile Basin Initiative.

Despite the progresses made since the establishment of the Nile Basin Initiative, the Arab Republic of Egypt and Sudan failed to sign the Cooperative Framework Agreement because of their disagreement concerning what should be stipulated in Article 14 (b). Upper riparian states need Article 14(b) to read as (b) "Not to significantly affect the water security of any other Nile Basin State"; whereas, Egypt and Sudan needed it to read as (b) "Not to adversely affect the water security and current uses and rights of any other Nile Basin state" (Tadesse, 2016). As a result of this irreconcilable difference, Article 14 (b) is left blank to be taken care of by the Basin Commission when established in the future. The effort of upper riparian states was to leveling the playing field for equitable and reasonable utilization Nile River. The fact that Ethiopia signed the Cooperative Framework Agreement and got other upper riparian states signed it as well reflects the increase of Ethiopia's bargaining power, the ability to set agenda and rule of the game (Cascão, 2009). The position of Egypt and Sudan, on the other hand, could not be taken as a surprise. Instead, it was consistent with the argument that cooperation between riparian states is difficult when there is already asymmetric gain (Furlong, 2006).

3.2. Major Hydro-communication Instances and Efforts in 2011-2023

2011 marked the launching of the construction of the Grand Ethiopian Renaissance Dam (GERD). The facilitating factors for Ethiopia to launching the construction of the Grand Ethiopian Renaissance Dam were availability of Abbay (Blue Nile) Master Plan Study, extended period of economic development and relative political stability of Ethiopia (International Crisis Group, 2019). Resorting to public finance mobilization strategy to fund the project and geographic power have also played priceless role.

Following the launching of the Grand Ethiopian Renaissance Dam construction, Egypt took a lot of wrong moves, but the most notable ones included the live broadcast of a discussion chaired by president Morsi in 2013 with Egyptian politicians drawn from seven political parties to intimidate to wage war on Ethiopia(Horn Affairs, 2013), stipulation of Article 44 of the 2014 constitution to securitizing the basin based on unfounded claim called Egypt's 'historic rights' on Nile, taking the matter to the Arab League time and again and appealing to the UN Security Council in July 2021..

Sticking to its principle of seeking equitable and reasonable utilization of the Nile River Basin, Ethiopia responded to all the wrong moves of Egypt accordingly. In other words, Ethiopia exerted hydro-communication efforts. For instance, what Ethiopia did on 17 February 2020 was intriguing as a major hydro-communication on Nile River Basin. When the Washington Tripartite Negotiation, which took place following the request of Egyptian President Abdel-Fattah el-Sisi made to Trump, then sitting president of US, to mediate the conflict over the Grand Ethiopian Renaissance Dam while Ethiopia wanted to keep the negotiations on a tripartite level(Widakuswara, 2019), was coming to be more of a problem than solution, Ethiopia held a consultative meeting with chief negotiators, stakeholders, technical experts and prominent Ethiopians presided by the Prime Minister, Abiy Ahmed in the Prime Minister Office.

As disclosed by the Office of the Prime Minister, the meeting discussed the upcoming negotiations on the dam (borkena, 2020). Ethiopia reacted to the call of US administration to sign drafted agreement by saying 'more time is needed for domestic consultations. Put simply, by emphasizing the need for domestic consultations, Ethiopia technically declined to sign the drafted agreement. This move was consistent with two-level games theory which argues that when there are issues different states make dialogue on and interact, the states simultaneously engage in two-level interactions, domestic and international, and in the former, state demand and interest is formed, and in the latter, effort is exerted to get national interest win a space(Putnam, 2009). This move of Ethiopia was also congruent with the notion that communication of stakeholders on transboundary river basin helps decision-makers to make functional, logical and rational decisions at the heart of the delicate cooperation between governments in transboundary water management issues(Willner, 2006). Furthermore, it is very consistent with the assertion that development projects and programs related to water require the participation and engagement of multiple stakeholders across sectors and all levels, and communication secures the participation, empowerment, and commitment of stakeholders(UN Water, 2013).

The Washington Tripartite Negotiation ridiculously went astray mainly because it was not based on any fundamental water management principle at the beginning, and the involvement of U.S. in the tripartite negotiation has increasingly shifted its role from being observer and advisor which was originally agreed up on to agreement drafter and commander, which were not part of its mandate. For instance, a statement titled "Statement by the Secretary of the Treasury on the Grand Ethiopian Renaissance Dam" released on 28 February 2020 by the U.S. Department of the Treasury in its last part said "*final testing and filling should not take place without an agreement."* Ethiopia responded to the released statement as "*as the owner of the GERD, Ethiopia will commence filling the GERD in parallel with the construction of the dam, in accordance with the principles of equitable and reasonable utilization and not causing significant harm*" (Mehari, 2020).

Few days after the release of the statement by the U.S. Treasury Department, Egypt took the matter to the Pan-Arab bloc to win support for its position i.e. objecting the Grand Ethiopian Renaissance Dam due to concerns it may significantly reduce its "traditional share" of the Nile waters. Then, supporting "Egypt's water rights on the Nile", the resolution of the Pan-Arab bloc made on 05 March 2020 accused Ethiopia of having taken "obstinate stance" on Grand Ethiopian Renaissance Dam(Addis, 2020). Ethiopia stoutly responded to this resolution through releasing statement, excerpt of which says that Ethiopia rejects the 'Resolution' in its entirety as the 'resolution' gives blind support to a member state without taking into consideration key facts at the center of the GERD talks(ENA, 2020).

Another case of hydro-communication effort to consolidate Ethiopia's practical move was what was done by the end of July 2020. Accompanied by subsequent demonstrations organized by the diaspora in foreign countries and citizens in Ethiopia, Ethiopians around the globe held rallies chanting slogans, "It is My Dam" and "One Voice for Our Dam"(Elias, 2021) when celebrating the first round dam filling of the Grand Ethiopian Renaissance Dam (GERD). These rallies were also to propagating Ethiopia's just cause with regard to utilizing the Nile River Basin to people around the world. Availability of instantaneous communication such as social media contributed a lot here. This is in line with the argument that while the state actors play commonly a key role in conducting hydro-diplomacy, civil society actors can significantly encourage diplomatic processes through their interaction(Keskinen & Rautavaara, 2014).

On 23 October 2020 while Trump, then sitting president of U.S., was announcing the opening of relations between Sudan and Israel, he, all of a sudden, gave a belligerent threat to Ethiopia concerning the Grand Ethiopian Renaissance Dam. The excerpt of what Trump said was the following:

> *…I had a deal done and they broke the deal that they can't do that... and they will end up blowing up the dam and I said… "blow up that dam" … we have cut off all payments and everything else to Ethiopia*(Al Jazeera English, 2020).

The cut off payments which could affect up to nearly $130 million in U.S. foreign assistance to Ethiopia was reported by Foreign Policy on 27 August 2020(Gramer, 2020).

Different bodies reacted to Trump's belligerent threat. For instance, Minister of Ministry of Foreign Affairs, Mr. Gedu Andargachew reportedly said "*The incitement of war between Ethiopia and Egypt from a sitting US president neither reflects the longstanding partnership and strategic alliance between Ethiopia and the United States nor is acceptable in International Law governing interstate relations*"(Addis & Tih, 2020). Prime Minister Office of Ethiopia, on its part, expressed:

> *Occasional statements of belligerent threats to have Ethiopia succumb to unfair terms still abound. These threats and affronts to Ethiopian sovereignty are misguided, unproductive, and clear violations of international law. Ethiopia will not cave in to aggressions of any kind, nor do we give recognition to a right that is based on colonial treaties*(ALJAZEERA, 2020)

When the second-round dam filling of GERD was approaching, Arab League held extraordinary meeting of Arab Ministers over the dam crisis in Doha on 15 June 2021 and released a resolution backing Egypt and Sudan. The resolution mentioned that Egypt and Sudan's water security is an integral part of Arab national security. It also mentioned that the Arab League rejects any measure that would undermine the water share of Egypt and Sudan, in reference to Ethiopia's planned second filling in July in the absence of an agreement between the three countries on the filling and operations of the dam. The resolution made call on the United Nations Security Council (UNSC) to intervene in the crisis. Moreover, in a press conference following the meeting Arab League Secretary-General Ahmed Aboul Gheit said that the Arab countries will press for the UNSC to hold an urgent session on the dispute. In response to the Arab League released resolution, the Ministry of Foreign Affairs of Ethiopia released a statement expressing its "dismay" by the resolution and describing the Arab League as "misguided". Mentioning that Ethiopia "categorically rejects the futile attempt by the League of Arab States to dictate terms regarding the filling of GERD, the ministry said that because of the league's egregious support to the baseless claims of Egypt and Sudan regarding GERD, the Arab League has already squandered its opportunity to play a constructive role(El-Din M., 2021).

Following the appeal made by Egypt and Sudan, few days after the resolution of Arab League, the United Nations Security Council demanded Ethiopia to brief the council with regard to the Grand Ethiopian Renaissance Dam, and then Minister of Ministry of Water, Irrigation and Electricity of Ethiopia, Sileshi Bekele presented a nineteen minutes speech defending Ethiopia's right and national interest on the basin in general and the Grand Ethiopian Renaissance Dam (GERD) in particular. Although this speech contained many major themes, it touched up on five fundamental points pertinent to this discussion. One of the points strongly mentioned was that the Security Council is not a legitimate place for GERD. Strong explanation about GERD as the contribution of each and every citizen of Ethiopia was the other point discussed in the speech. The fact that GERD will be important to get millions of Ethiopians from the devastating impoverishment and sufferings was also presented. Moreover, argument indicating that Egypt and Sudan have far better water infrastructure compared to Ethiopia was presented. Furthermore, strong comment that the council will face challenges if it consents to the path proffered by Egypt and Sudan was forwarded. From the whole discussion made, it was learned that the Security Council staged two diametrically opposite philosophies: 'African Solutions to African Problems' and 'Water for Cooperation' advocated by Ethiopia vis-à-vis Solution from Global Powers for African Problems and Cooperation for water advocated by Egypt.

Even in the wake of the second and third phase dam filling and electricity generation of first and second turbines on 20 February 2022 and August 2022 respectively, the council of Arab Foreign Ministers passed a 'resolution on 10 March 2023' "backing Egypt's water rights on the Nile" and threatened that it decided to take the matter to its meeting with European foreign ministers in June. Ethiopia, as usual and accordingly, reacted to this (Ethiopian Monitor, 2023). Ethiopia reacted to this by mentioning three important points. First, Ethiopia reiterated that the Nile River and all the riparian countries are located in Africa and the African Union-led process was taking care of it. Second, Ethiopia condemned that this body was serving as the spokesperson of one state, disregarding basic principles of international law. Third, Ethiopia stressed and warned that such attempts to politicize the issue of GERD were not based on facts or supported by law, and they neither advanced friendly relations nor supported the efforts to arrive at amicable solutions(Ethiopian Monitor, 2023). This new reactive phase strategy of Ethiopia was equivalent to what is labeled as contesting the existing hydro-hegemony and status quo and enhancing the creation of level playing field(Cascão, 2009) for equitable and reasonable utilization of the Nile River Basin.

Following the talk held in Cairo on 13 July 2023 between President Abdel Fattah el-Sisi and Ethiopia Prime Minister Abiy Ahmed who aimed to reach an agreement on the 'filling and annual operation of the Grand Renaissance Dam' within four months, it was agreed that the tripartite negotiation, which was off for some time, should resume(AP, 2023). Consequently, four round tripartite negotiations, two in Cairo and two in Addis Ababa, held, but agreement could not be reached(Sahlu, 2023). The latest tripartite negotiation was held December 17-19, 2023. There has been no tripartite negotiation going on since this time. However, there is a strong hope that the parties will soon come to the table and resume negotiation. This strong hope is held based on the longstanding fact concerning interaction over transboundary river basins on one hand and experience gained from the tripartite negotiation on the other hand. The long standing fact concerning interaction over transboundary river basins is that conflict and cooperation can co-exist (Zeitoun & Warner, 2006) as neither continuum nor mutually exclusive to each other. Negotiation while undertaking dam construction, which was witnessed by the 2015 Tripartite Agreement, is the experience gained.

4. CONCLUSION

Recorded secular history showed that Ethiopia fought for more than 120 years, 1902-2023, to reach a stage to start utilizing Nile River Basin through constructing mega project on it. Ethiopia's hydro-communication efforts on Nile River Basin in those years were congruent with the international water law and aimed at, consecutively, defending the basin from colonial powers, resisting, though not successful at that time, the formation and continuation of Egypt's hydro-hegemony and reacting to multiple wrong moves made by Egypt and its multiple allies to halt Ethiopia's progress to utilizing the basin. Hydro-communication efforts of Ethiopia registered remarkable progress. Facilitating factors for these were two types: national and global. The national level facilitating factors were consistent position of Ethiopian governments, produced knowledge on the basin, geographic power and public funding. The global level facilitating factors were the developments happened with regard to utilization of transboundary river basins. These developments include the UN Watercourse Convention and the need for participation of stakeholders along with decentralized management for transboundary river basin management. Availability of instantaneous communication that includes social media has also played immeasurable enabling role in voicing the right of Ethiopia with regard to the Grand Ethiopian Renaissance Dam. Hydro-communication effort of Ethiopia has transformed from being completely reactive in 1902 to 1990s to being influential since 1999. Similarly, bargaining and ideational powers of Ethiopia were growing. As discussions and negotiations on transboundary river basin are never ending process in general, and Ethiopia continues facing huge pressure in particular, hydro-communication efforts of Ethiopia should be upgraded to strategic communication level to withstand the pressure and completely ensure equitable and reasonable utilization of the Nile River Basin.

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