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Spatiotemporal Variability of Reference Evapotranspiration Estimation and Mapping for Arjo-Dedessa Sugar Factory and Its Surrounding

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Abstract

Evapotranspiration, which represents a significant amount of moisture lost from a catchment, is an important parameter in the hydrologic cycle. However, it was challenging to determine the quantity due to the non-uniform distribution of meteorological stations and data in adequacy, which can be solved by an interpolation technique. Accordingly, the objective of this study was to estimate the spatiotemporal variability of reference evapotranspiration for the Arjo Dedessa sugar factory and its surroundings. ArcGIS, CROPWAT, and XLSTAT were the materials used. GIS was utilized to map the ETo variability, the XLSTAT2019 software was used to fill in the missing data, and the ETo was calculated using the CROPWAT. The data came from the Ministry of Water, Irrigation, Electricity, and Energy, as well as the National Meteorological Service Agency. Fourteen meteorological stations were identified, and data from 10 of them was selected for study after their quality was verified. The ETo map was created using the elevation and position of each station. Over the whole study area, the ETo values were interpolated using Kriging. The results show that the yearly spatial average daily ETo ranges from 3.67 millimetres to 4.65 millimetres of water depth. Because of the cold climate and heavy precipitation, the ETo value was lower at higher elevations. However, because of the warm temperature, it was higher in low-altitude places. Throughout the year, the monthly ETo temporal distribution has varied. During the summer, daily ETo values ranged from 3.10 to 3.39 millimetres, with a mean of 3.24 millimetres.

Keywords: Depth of water • Eto • Geo stastical • Interpolation • Kriging • Millimetre

Introduction

Since it represents a significant amount of moisture lost from a catchment, evapotranspiration is an important parameter in the hydrologic cycle. As rain falls on the earth and soaks into the soil, plants absorb it and then transpire it through their leaves, stems, flowers, and roots. Because of its importance in determining crop water use efficiency in agricultural ecosystems, accurate calculation of the reference crop evapotranspiration (ET_0) is being explored. Appropriate models must account for activities such as soil water intake, plant water transport, and water loss [1]. Determining the evaporative demand of the atmosphere, known as the reference evapotranspiration and the crop coefficient, is a vital aspect in estimating crop water requirements [2]. Estimating the evaporative demand of the atmosphere was crucial in irrigation management [3]. Although evaporative demand can be measured both directly and indirectly, direct measurement is both inconvenient and costly [4]. As a result, various methods for estimating ETO using climate data have been devised [5, 6]. Despite the differences in their climatic data requirements, most of the methods fall short of the requisite accuracy in calculating the value of ETO for any place. The availability of climatic data and the amount of accuracy necessary strongly determine the method of choice. Due to its superior results when compared to other models in various parts of the world, the FAO-56 Penman-Monteith model has been recognized as the most precise by an international scientific community [7, 8]. The FAO-56 Pen Man [6] estimates reference ETo using weather data such as maximum and minimum temperature, solar radiation, sunlight hours, wind speed, and relative humidity. The key issues confronting researchers, irrigation agronomists, water resource planning and management, and water resource policymakers include a lack of meteorological data, a discontinuity in data records, and a low station density. According to [9] the problem of low station density can be solved by using spatial interpolation techniques to estimate values in areas where measurements are unavailable or weather data is limited, and then extending the findings from the points of measurement to a regional scale. Therefore, the objective of this study was to estimate and map the spatial and temporal variability of reference evapotranspiration in Arjo Dedessa Sugar Factory and the surrounding areas as a basis for studying the hydrology of the area.

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Material and Methods

Description of the study area

The study area is located at Western Ethiopia of Oromia Regional State in Eastern Wollega, Ilu Ababora and Jimma Zones at 540 kilometers from the capital through the route of Addis Ababa-Jimma-Nekemte roads. The altitude of the area is 1,350 meters above mean sea level. Geographically, it is found 7°36'00" up to 9° 36'00" North and 35° 32'00" up to 37 °34'00"East **(Figure 1)**.

The study areas have a mean annual rainfall of 1400 millimetres. Its rainy season extends from May to October. The monthly mean maximum temperature varies from 21.16 °C up to 33.75 °C and the monthly mean minimum temperature varies from 7.01 °C to 14.89 °C. The rain fall distribution of the study area reveals that the distribution is not uniform in some months; there is very low or even no rainfall for up to four to five months continuously, and in some months, there is continuous rainfall, mainly during the summer season.

Material used for conducting the study

Arc GIS 10.4.1, CROP WAT 8.0, and XLSTAT software were utilized to conduct this study. The spatial and temporal variability reference evapotranspiration was mapped using GIS. Since the meteorological data has a missing value in some months, the XLSTAT2019 software was used to fill in the blanks [10]. The reference evapotranspiration was calculated using the CROPWAT 8.0 model.

Data collection and sources of data

Secondary data has been collected from the responsible organization. They were collected from the Ministry of Water, Irrigation, Electricity and Energy

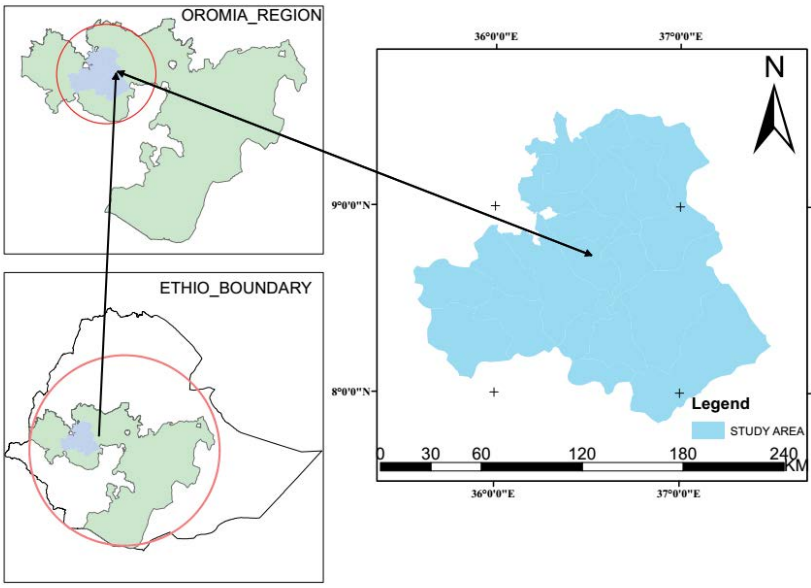

Figure 1. Geographical location of the study area.

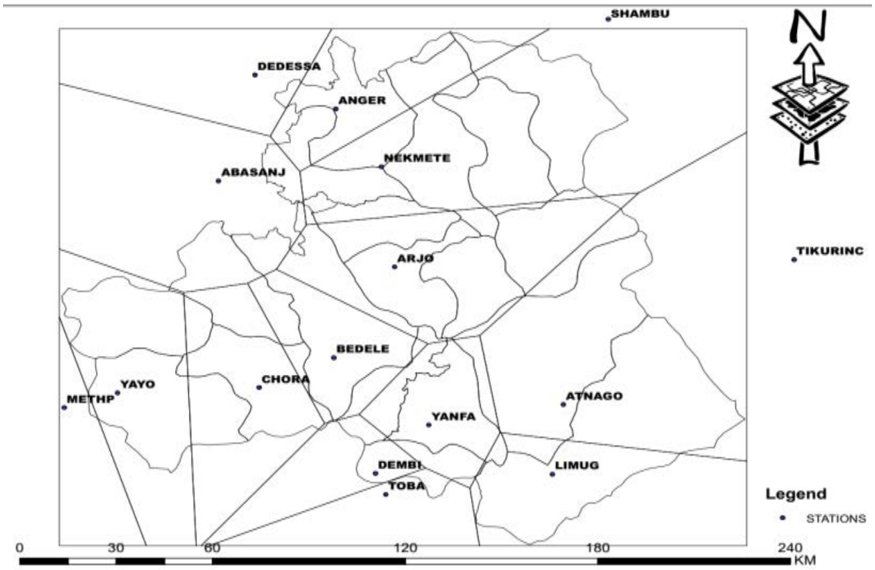

Figure 2. Location of meteorological station.

(MoWIEE) and the National Meteorological Service Agency (NMSA). The required data for this study includes digital elevation models (DEMs), shape file and meteorological data.

Method of estimating and mapping the reference evapotranspiration

Fourteen (14) meteorological stations in Oromia regional states, namely the Abasan Joger, Anger, Arjo, Atnago, Bedele, Chora, Dedessa, Dembi, Limu-Genet, Metu-Hospital, Nekemite, Toba, Yanfa, and Yayo stations were delineated. From these stations, meteorological data from ten (10) stations, namely Anger, Nekemt, and Arjo in the Northern, Bedele, Yanfa, and Dembi in the Southern, Atinago and Limu-Genet in the Eastern, and Yayo and Chora stations in the Western of the study area, were used for analysis **(Figure 2 and 3)**. The basic data quality checking, mainly filling the missing data, checking the consistency of the rainfall, and checking the homogeneity of the data, was done (Figure 4).

Before estimating the reference evapotranspiration, the method's accuracy and reliability, as well as the availability of data, were assessed. For estimating reference evapotranspiration, certain equations and established processes are recommended. The International Commission for Irrigation and Drainage (ICID) and the Food and Agriculture Organization of the United Nations (FAO) expert consultation on the revision of FAO methodologies for crop water requirements recommended that the FAO56-PM Penman-Monteith equation (FAO56-PM) be used as the standard method to estimate ETo. It gives the most accurate estimation of ETo and is one of the most reliable strategies for accounting for all atmospheric changes [11,12]. Accordingly, utilizing meteorological data and the FAO Penman-Monteith method in the CROPWAT 8.0 model was used for estimating the ETo.

The elevation, latitudinal, and longitudinal location of each station, as well as the related estimated (measured) data at each station, was utilized to create the reference evapotranspiration map. On the delineated DEM of the study region, these data were loaded into the GIS's geostatistical software and predicted using the package's kriging approach. The collected data was then used to create a linear regression equation using the elevation of the station.

The ETo was calculated from the linear regression equations as the difference between measured (observed) and predicted values at the station locations. Then the ETo value was interpolated using ordinary Kriging over the whole study area. A spatial grid was developed from the location of each station and the DEM. The ETo for each month was interpolated by the kriging using the geostastical tool of the GIS software. The final estimation of ETO at any location was obtained by adding the interpolated map and regression kriging map of the study area, from where all the necessary meteorological data were collected. Finally, the reliability and applicability of the geostastical tool for

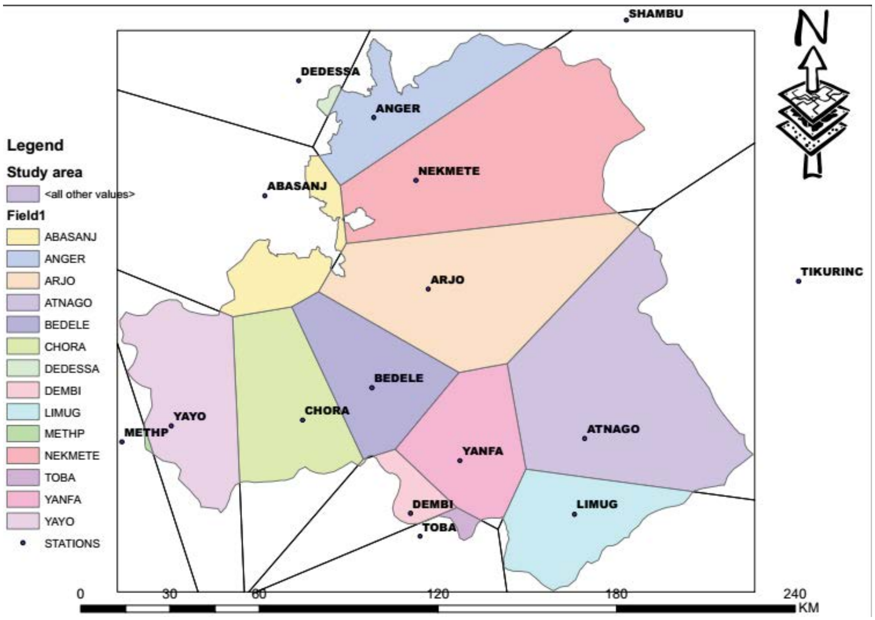

Figure 3. Selected meteorological stations using thiesson polygon.

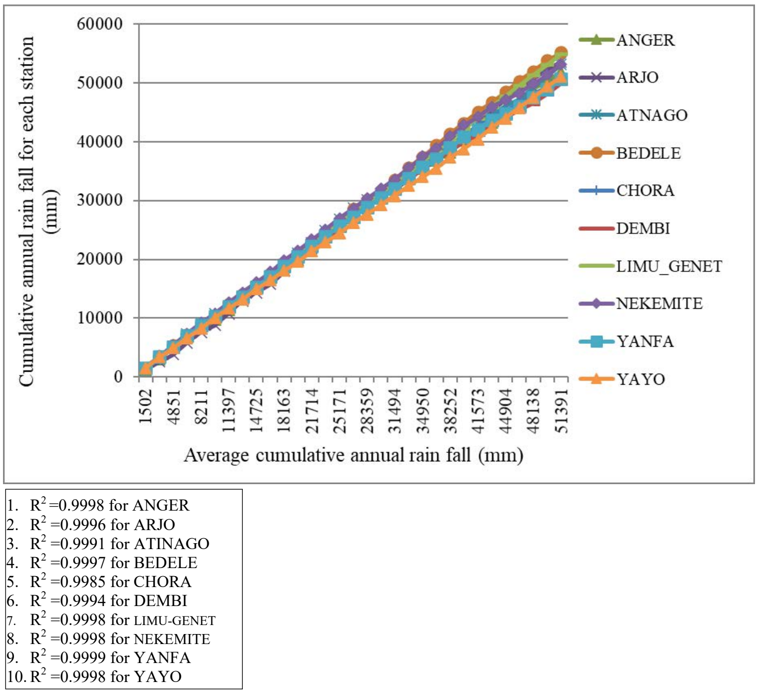

Figure 4. Double Mass Curve for the Stations of the study area.

the respective mapped reference evapotranspiration were correlated by the measured data and predicted value.

Result and Discussion

Reference evapotranspiration of the study area

The reference evapotranspiration of the station at the Northern part of the study area reveals that the daily minimum and maximum reference evapotranspiration at Anger station was 4.07 millimetre and 5.23 millimetre, at Nekemt station it was 3.27 millimetre and 4.65 millimetre and at Arjo station it was 3.49 millimetre and 4.36 millimetre depth of water, respectively. At Southern part of the study area, the daily minimum and maximum reference evapotranspiration at Bedele station was 3.20 millimetre and 4.26 millimetre, at Yanfa station it shows 3.21 millimetre and 4.32 millimetre and at Dembi station it was 3.10 millimetre and 4.25 millimetre depth of water, respectively.

The daily minimum and maximum reference evapotranspiration at Yayo station were 3.48 millimetres and 4.23 millimetres of water, respectively, in the western half of the research region, and 3.31 millimetres and 4.23 millimetres of water at Chora station. The daily minimum and maximum reference evapotranspiration were 3.30 millimetres and 4.32 millimetres, respectively, in the eastern half of the research region, and 3.22 millimetres and 4.35 millimetres at Limu-Genet station. The research area's yearly average ETo ranged from 3.67 millimetres to 4.65 millimetres depth of water. ETo value was smaller in high altitude areas, because it is related with cold climate and high precipitation. However, ETo value was higher in low altitude areas, hence it is related with warm climates. Thus, the spatial variability of predicted ETo value caused by varied elevation. The decrease of ETo with altitude is due to the decrease of air temperature with altitude. The lower ETo in the high-altitude areas was contributed from altitude difference, the areas were characterized by high altitudes as compared to lowland areas.

According to Um et al (2017), with increasing elevation, the air temperature decreases and RH increase, thus, the ETo generally decreases. This means the greater altitude of an area is the smaller temperatures, as altitudes increase the temperature decreases because temperature is the major climatic factor, which affects ETo [6] ETo vary with altitude, every 1000 m rise in altitude will result in 10% ETo reductions [5]. The monthly ETO temporal distribution has shown some variations throughout the year. The temporal distributions were relatively similar for monthly and annual ETo values (Table1).The highest daily ETO values were predicted from January to April and the average values range from 4.34 to 5.23 millimetre, which corresponds to dry season. Of all months, the highest daily ETo value was estimated in March and the value varies from 4.65 to 5.23 millimetre.

The highest ETo value in March is due to warm air and low humidity. During the dry season, a high amount of energy was available when temperatures were high. Daily ETo values during the summer season (July to September) were relatively low, and the values ranged from 3.10 to 3.39 millimetres, with a mean of 3.24 millimetres, since the summer season is the main rainy season in the study area. Of these months, the smallest ETo value was predicted during the rainy month of July, and the values varied from 3.10 to 4.28 millimetres daily. ETo during July had a reduction of 34.14% as compared to April. During the rainy season, the low ETo value was caused by lower air temperature and higher humidity as a result of the continued rain fall [14].Described that the evapotranspiration rates tended to drop to low levels when the air around the plants became too humid during the rainy season.

The temporal variation of ETo was also observed due to changes in solar radiation as a result of a change in the season. Low ETo values were obtained during the summer when it was cool, cloudy, and humid, whereas they were high during the winter when it was hot, sunny, and dry. The monthly ETo values vary in the same pattern as the maximum air temperature and sunshine hours, but vary in different patterns with rainfall and relative humidity [13] have also justified that, in low land parts of Ethiopia, the difference in ETo is due to cloud cover, temperature, and relative humidity **(Table 1)**.

Reference evapotranspiration mapping of the study area

According to the geostastical map of the study area, the kriging method reveals that the daily spatial variation of the average reference evapotranspiration was in the range of 3.74 millimetres up to 3.96 millimetre depth of water **(Figure 5)**. The correlation (R^2) value between the measured and the predicted value was 0.9972, and this shows that they have a strong statical relationship **(Figure 6)**.

As shown in figure 5 below, the spatial reference evapotranspiration was relatively higher in the northern part of the study area and lower in the southern part of the study area. The advantage gained because of the spatial mapping was that it avoided the confusion that would be caused by using a single meteorological station by only considering the proximity of the station to the study area. Additionally, the spatial mapping of the reference evapotranspiration can help to use the data in the absence of a meteorological station in the study area for specific agricultural cultivation.

The temporal variations of the average daily reference evapotranspiration map reveal that the maximum reference evapotranspiration was 5.42 to 5.53 millimetres, which occurred during the month of March, and the minimum was 3.088 to 3.19 millimetres, which occurred during the month of July. The highest reference evapotranspiration was because of the warm air temperature and low humidity. The relatively lower reference evapotranspiration was because of the rainy season. This low ETo value during the rainy season was due to the lower air temperature and higher humidity as a result of continuous rain fall. Evapotranspiration rates tended to drop to low levels when the air around the plants was too humid during the rainy season [14].

Table 1. Monthly daily average ETo of the stations.

No	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		ETo	ETo	ETo	ETo	ETo	ETo	ETo	ETo	ETo	ETo	ETo	ETo
1	Anger	4.34	4.61	5.16	5.23	5.03	4.56	4.28	4.33	4.34	4.3	4.14	4.07
2	Arjo	3.68	4.01	4.31	4.36	4.18	3.82	3.67	3.69	3.77	3.82	3.58	3.49
3	Atinago	3.78	4.07	4.32	4.3	4.05	3.7	3.3	3.35	3.67	3.97	3.71	3.52
4	Bedele	3.61	3.91	4.18	4.26	4.05	3.57	3.2	3.31	3.66	3.81	3.58	3.44
5	Chora	3.59	3.86	4.13	4.23	4.01	3.59	3.31	3.42	3.72	3.9	3.65	3.35
6	Dembi	3.72	4.08	4.25	4.16	3.89	3.63	3.1	3.16	3.39	3.82	3.61	3.53
7	Limu-Genet	3.72	4.18	4.35	4.27	4.04	3.74	3.16	3.22	3.46	3.91	3.67	3.57
8	Nekemte	4.01	4.41	4.64	4.65	4.34	3.64	3.27	3.31	3.48	3.77	3.72	3.7
9	Yanfa	3.72	4.06	4.32	4.31	4.05	3.66	3.21	3.3	3.6	3.9	3.62	3.49
10	Yayo	3.7	3.96	4.23	4.21	4.19	3.68	3.48	3.57	3.84	3.97	3.74	3.5

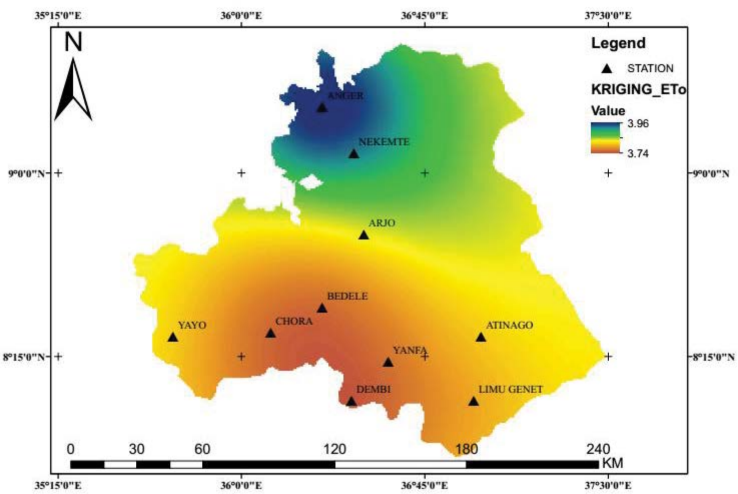

Figure 5. Spatial variability of Reference evapotranspiration of the study area.

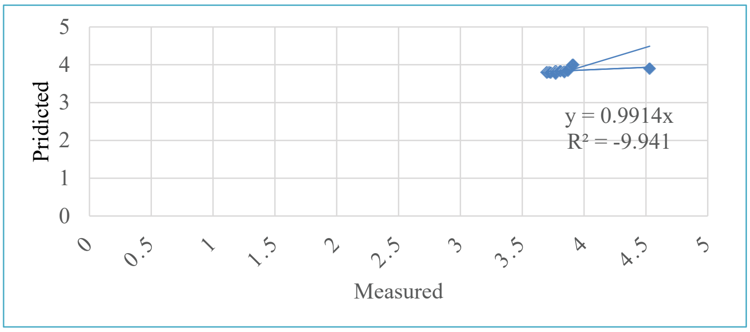

Figure 6. Co-relation of the measured and predicted value of reference evapotranspiration.

Conclusion

The annual average daily ETo of the study area generally range from 3.67 millimetres up to 4.65 millimetres. Even though the average daily ETo was between 3.67 millimetre and 4.65 millimetres, there was a maximum ETo of 5.23 millimetres. The temporal distributions were relatively similar for monthly and annual ETo values. The dry season was predicted to have high ETo values from January to April, with average values ranging from 4.34 to 5.23 millimetres. Of all the months, the highest ETo value was predicted in March, and the value varied from 4.65 to 5.23 millimetres. The ETo value was lower in high-altitude areas, because it is associated with a colder climate and higher precipitation. However, ETo values were higher in low-altitude areas, hence they are associated with warmer climates. Thus, the spatial variability of the predicted ETo value is caused by varied elevation. The estimated and mapped reference evapotranspiration is advantageous to use for hydrologists and irrigation agronomist in an area that has in adequate or inconsistent meteorological data. The estimated reference evapotranspiration can be used to determine crop water and irrigation water requirement of crops by changing a specific property of crops and crop coefficient (Kc).

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