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Determination of Optimal Irrigation Using Soil Moisture Depletion on Yield and Water Productivity of Potato (Solanum tuberosum L.) at Odo Shakiso District, Southern Ethiopia

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Abstract: Irrigation technologies that save water are necessary to ensure the economic and environmental sustainability of agriculture. Accurate irrigation planning is critical to improving irrigation efficiency. Therefore, this activity aimed to evaluate the responses of potato plants to the irrigation system (when and how much) and to determine the water productivity (WP) under optimal irrigation system. During the 2020 and 2021 irrigation season, a field trial of five irrigation treatments (20% ASMDL, 40% ASMDL, 60% ASMDL, 80% ASMDL and 100% ASMDL (FAO recommended ASMDL) irrigation) was conducted in Odo Shakiso district. The experiment was set up in a randomized complete block design (RCBD) with three repetitions. For the Irrigation Treatment at Allowable Soil Moisture Depletion (ASMDL), irrigation was scheduled when 35% of the total available water was depleted. Results showed that potato tuber yield, number of tubers per plant, and water productivity were significantly affected between treatments ($P<0.05$). Plant height, tuber weight and non-marketable tuber yield did not vary significantly between treatments. The highest marketable tuber yield (32.91 t ha^{-1}) was achieved using irrigation water with 100% ASMDL. Reducing soil moisture loss from the recommended level (0.35) did not increase water productivity. However, no significant difference in water productivity was observed between irrigation water application at 60% of the ASMDL and irrigation water application at 100% of the ASMDL (FAO recommended depletion limit). Therefore, it can be concluded that the application of the FAO recommended ASMDL can provide the highest marketable tuber yield and water productivity of potatoes in the study area and in a similar agro ecology. Therefore, further investigation and verification work under different climatic conditions is recommended.

Keywords: Allowable Soil Moisture Depletion Level (ASMDL), Potato, Irrigation Regime, Water Productivity (WP)

1. Introduction

When population was rare and drought was not as common as it is today, rain-fed agriculture could, and did, support Ethiopia's population. But rain-fed cultivation alone in the highlands will not feed the population adequately, even in good years [10]. The efficiency of precipitation, even in areas of high precipitation, is hindered by its irregular occurrence and uneven distribution. Production using the available water resources in the form of irrigation is therefore vital to complement rain-fed cultivation and also produce in non-rainy seasons. For countries like Ethiopia, which are always affected by drought, famine and poverty, irrigation plays a very significant role to compensate for frequent food shortages, since irrigation is the most common means of ensuring sustainable agriculture and managing with periods of insufficient rainfall [4]. Water is the most key input in crop production [6]. Plants should take adequate watering at the various stages of plant growth in order to achieve acceptable yields. The full benefit of crop production technologies such as high-yielding varieties, use of fertilizers and a wide range of cultivation and plant protection measures can only be achieved if an adequate water supply is guaranteed. On the other hand, the optimal use of irrigation can only be achieved if other means of production and technologies are made available [5]. Therefore, irrigation is an alternative way to provide plants with these imperative factors. Potato (Solanum tuberosum L.) yield is reduced by both over- and under-watering. Deviating as little as 10 percent from the optimal water application for the growing season can result in a reduction in yield [3, 7, 14]. Yield deteriorations due to overwatering can be credited to poor soil aeration, increased disease problems, and nitrogen leaching from the shallow root zone of crops.

Plants that are kept within acceptable stress levels throughout their growth cycle have the potential to produce optimal, high-quality yields. The goal of irrigation scheduling is to have soil moisture within a favorite range, typically between field capacity (full point) and a predetermined refill point for optimal growth. For an irrigation schedule to be effective, it must tell us when and how much water to apply. Irrigation scheduling is one of the most important tools for developing best management practices for irrigated areas.

The yield and quality of the potatoes hurt due to insufficient water supply and incorrect irrigation planning. The available irrigation water must be used in such a way that it agrees to the water requirements of the crops. Knowing the water requirements of crops is a significant practical consideration for improving water use efficiency in irrigated agriculture. Water use efficiency can be enhanced by proper irrigation scheduling, which is basically controlled by crop evapotranspiration (ETc).

In the Shakiso areas, vegetation crops are grown by furrow irrigation systems in small farmers, and most of the irrigation water management is based on the traditional method, with farmers irrigating for as long as the water is available, nevertheless of whether it is above or below optimum is the water requirement of the plants. Therefore, this activity aimed to evaluate the responses of potatoes to the irrigation system (when and how much) and to determine the water productivity (WP) under optimal irrigation system.

2. Materials and Methods

2.1. Description of the Study Area

The experiment was conducted for two consecutive years (2020 and 2021) in Odo Shakiso District by Bore Agricultural Research Center. The area is characterized by a bimodal rainfall pattern with the extended rainy season (known locally as Hagayya) and a short rainy season (known locally as Ganna). The District has geographical location of 5°2'29”-5°58'24” northing latitudes and 38°35'0” - 39°13'38” easting longitudes. The district is characterized by three agro climatic zones, namely highland (bada), which accounts for about 33%, midland (badadare), which accounts for about 47%, and lowland (gamoji), which accounts for about 20% of the district's area. Most of the district's land surface consists of ups and downs of land surface with an elevation between 1500 and 2000 m above sea level. in the larger southern part of the northwestern part. Plains, dissected hill plateaus and mountains as well as valleys and gorges shaped the relief of the district. The average annual precipitation is about 900 mm and the average annual temperature is 22.50 °C. The soil structure class of the test area is clay with a pH of 6.95. The most commonly grown crops in the district are wheat, barley, corn, teff, kidney beans, chickpeas, flaxseed, canola, fruits and vegetables (District Statistical Summary 2014/15).

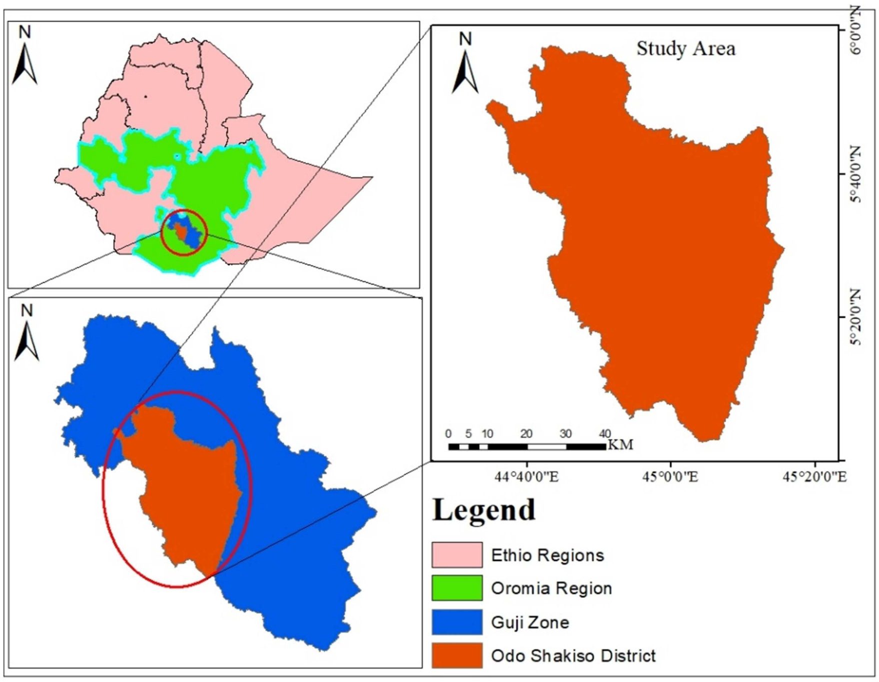

Figure 1. *Location Map of the study area.*

2.2. Experimental Set up and Treatment Application

Irrigation treatments included five levels of soil water depletion depending on FAO soil moisture depletion. Experimental treatments were set up in three replicate randomized complete block design (RCBD) in which soil moisture depletion levels (SMDL) were randomly assigned to experimental plots.

Table 1. *Treatment setting for field experiment.*

Treatment	Description
ASMD1	20% ASMDL
ASMD2	40% ASMDL
ASMD3	60%ASMDL
ASMD4	80% ASMDL
ASMD5	100% ASMDL*(FAO recommended)

Where: ASMDL- allowable soil moisture depletion level

2.3. Experimental Procedure and Management Practice

Potatoes (S. tuberosum L.) of the Zemen variety were planted in two consecutive years (2020 and 2021). Planting was done manually on a test area of 3.75 x 4.8 m (18 m^2). The distance between plants, plots and replicates was 0.3 m, 1 m and 1.5 m, respectively. Potato seeds were planted in six rows with four rows harvestable. All plots received the same fertilizer rates consisting of 150 kg ha-1 urea and 242 kg ha-1 NPS based on local fertilization recommendations. The full dose of NPS was applied at planting, while urea in a split form was applied half at planting and the rest 45 days after planting. Irrigation scheduling was based on percentage depletion of available soil water in the root zone. Soil water levels were monitored using the gravimetric method of determining soil moisture content. A specified amount of irrigation water was applied to each plot using a standard 3-inch dividing gutter. All agronomic practices were implemented at a time of need.

2.4. Soil Sampling and Analysis

Soil samples were collected from the experimental field at two depths (0-30 cm and 30-60 cm) to determine soil texture, PH, electrical conductivity (EC), organic carbon (OC), bulk density (BD) and field capacity. FC) and permanent wilting point (PWP). The particle size distributions in the soil profiles were determined using the hydrometric method [13]. The pH of the soil was measured in a soil-water mixture of 1: 2.5 using a pH meter. The soil electrical conductivity of the study area was determined by computing the conductivity of saturated soil extract with an electrical conductivity meter. The organic carbon content was determined by the titration method using chromic acid (potassium dichromate + H_2SO_4) digestion according to the method [15]. The bulk density of the soil was determined using undisturbed soil samples using a core sampler. The field capacity and permanent wilting point of the soil were analyzed in the laboratory using a pressure plate apparatus at a pressure of 1/3 bar (for field capacity) and 15 bar (for permanent wilting point). The soil was also examined for infiltration using double ring Infiltrometers.

The gravimetric method was used to determine moisture content and then changed to volumetric water content by multiplying by soil bulk density and bulb root depth to give the field/current moisture available at that time

$$\theta_{dw} = \frac{w_{ws}-w_{ds}}{w_{ds}} \quad (1)$$

Where Wws = weight of wet soil (g), θdw = water content expressed on weight basis in (%) and Wds = weight of dry soil (g)

2.5. Crop Water Requirement

Mainly 15 years of climate data (2004-2018) were collected, including monthly data on maximum and minimum temperature, relative humidity, precipitation, wind speed and hours of sunshine. Daily ETo values (mm/day) were calculated from the collected data using the Windows model FAO CropWat 8.0. Kc values were taken from FAO Irrigation and Drainage Paper No. 56 [1]. Then the water requirements of the crops were calculated from the following equation:

$$ETc = ETo \times Kc \quad (2)$$

Where:

ETc = crop water requirement (mm/day)

ETo = estimation of reference crop Evapotranspiration in mm/day and Kc = crop coefficient

2.6. Determination of Irrigation Requirement and Irrigation Scheduling

The total available water (TAW) for crop use in the root zone was calculated from field capacity and permanent wilting point using following expression [1]

$$TAW = 1000 \sum(\theta FC - \theta PWP) * BD * Zr \quad (3)$$

Where: TAW: volumetric total available water in the root zone (mm/m) FC: volumetric moisture content at field capacity (m^3 /m^3) and PWP: volumetric moisture content at permanent wilting point (m^3 /m^3). BD: bulk density (gm. /cm^3)

Then, RAW (mm) which is equal to net irrigation depth (dnet) was computed from total available water using the following equation [1]:

$$RAW = TAW * \rho \quad (4)$$

Where: RAW in mm which is equal to net irrigation depth (mm) TAW: Total available water ρ : water depletion fraction/management allowable depletion (%), for onion (ρ =0.25). Then, irrigation interval was computed from the expression:

$$Iterval\ (days) = \frac{RAW}{ETc} \quad (5)$$

Where, RAW in mm which is equal to net irrigation depth (dnet) and ETc in mm/day is crop evapotranspiration.

Then, gross irrigation requirement (dg):

$$dg = \frac{dnet}{Ea} \quad (6)$$

Where, dg in mm and Ea is the field irrigation application efficiency of a short, end diked furrow was taken as 60% [2].

The amount of water applied to the experimental field was measured by 3-inch Parshall flume. The time required to deliver the desired depth of water into each plot was calculated using the equation [8]:

$$t = \frac{dg \times A}{6 \times Q} \quad (7)$$

Where: dg = gross depth of water applied (cm) t = application time (min) A = Area of experimental plot (m^2) and Q = flow rate (discharge) (l/s)

2.7. Irrigation Water Application

The ETo values estimated using the CROPWAT model based on climatological parameters have to be adjusted to the actual crop. A 3 inch standard Parshall flume was installed near the trial field to measure irrigation water applied to individual plots. A stop watch was used to measure the flow into each plot and the time required to immediately inject the desired depth of water into the plot. For the calculated time, water was let into the plot and each furrow. Immediately after reaching the desired depth, the plots were closed with the banks of the canal to prevent water from entering the plots.

2.8. Data Collection

Representative four-row potato plant samples were harvested after plant height was recorded and collected per plot. Data on potato yield and yield components such as plant height, tuber weight, number of tubers per plant, non-marketable tuber yield and marketable tuber yield were collected.

2.9. Water Productivity

Water productivity was estimated as the ratio of potato tuber yield to the crop's total water consumption through evapotranspiration (etc.) during the growing season and calculated using the following equation (Zwart and Bastiaanssen, 2004).

$$CWP = \frac{Y}{ET} \quad (8)$$

Where, CWP is crop water productivity (kg/m³), Y potato tuber yield (kg/ha) and ET is the seasonal crop water consumption by evapotranspiration (m³/ha).

2.10. Data Analysis

All necessary data collected were managed properly using the Genstat software 18th edition. When the treatment effect was found significant, the mean separation was tested using least significant difference (LSD) at 5% probability level.

3. Results and Discussion

3.1. Analysis of Selected Soil Physical Properties

The soil result of the study area indicated that the average composition of sand, silt and clay fractions was 35%, 32% and 33% respectively. Based on USDA soil texture classification, determination of percent particle size for the test site indicated that the soil texture could be classified as clay loam. The average bulk density of the study area was 1.36 g/cm3, which is below the critical threshold of 1.45 g/cm3, and it was suitable for crop root growth. The average moisture content of the test site soils was 25.8% at field capacity and 18% at the permanent wilting point. As indicated in (Table 2), the average total water volume available was 106 mm/m.

Table 2. *Results of selected soil physical properties.*

Soil Depth (cm)	BD (g/cm³)	FC (%)	PWP (%)	TAW (mm/m)	Textural Class			
					%Sand	%Silt	%Clay	
0-30	1.34	25.8	18.0	109	38	36	26	Loam
30-60	1.37	25.4	17.9	103	32	28	40	Clay
Average	1.36	25.8	18	106	35	32	33	Clay loam

Where: BD- bulk density, FC- field capacity, PWP- permanent wilting point, TAW- total available water

3.2. Analysis of Selected Soil Chemical Properties

The average pH of the trial site was within the recommended range based on the analyzed soil profile with an average value of 6.95% (Table 3). The average soil organic carbon and organic matter content averaged 1.64% and 2.82%, respectively, over the 60 cm depth of the soil profile. The average electrical conductivity of a test floor is 0.089 ds/m. In general, according to the USDA soil classification, soils with an electrical conductivity of less than 2.0 dS/m at 25°C and a pH of less than 8.5 are considered normal. The soils in the study area were therefore normal soils. The soil infiltration rate at the study site was 6 mm/hour.

Table 3. *Results of selected soil chemical properties.*

Soil Depth (cm)	pH (H_2O)	ECe (dS/m)	%OC	%OM
0-30	6.5	0.430	1.97	3.40
30-60	7.4	0.192	1.30	2.24
Average	6.95	0.311	1.64	2.82

Where: OC-Organic carbon, EC: Electrical conductivity

3.3. Effect of Soil Moisture Depletion Levels on Yield, Yield Components and Water Productivity of Potato

Plant height (cm): Analysis of variance showed that the effect of irrigation water application at different allowable soil moisture losses on potato plant height was not significantly different (Table 4). Among treatments, the FAO recommended available soil moisture removal, which recorded maximum plant height (73.73 cm) and minimum height (68.10 cm) under 60% ASMDL (Table 4). Although the same results were reported by [9] who concluded that a 100% ASMDL resulted in a plant height of 76.83 cm in potatoes whereas a 60% ASMDL resulted in a plant height of 75.0 cm led.2) Average tuber weight (g): Uniform Although there is no statistically significant difference between the treatments, the higher average tuber weight of potato (164.2 g) was noted with the application of irrigation water at the FAO-recommended ASMDL, while the lightest average tuber weight (129.2g) was recorded when treated with 40% ASMDL irrigation water application (Table 4).

Number of tubers per plant: The overall two-year result of the experiment showed that the number of tubers per potato plant was significantly ($p<0.05$) affected by different optimal irrigation treatments. Data on the number of tubers per potato plant showed that a maximum value of 20.07 was achieved by irrigation water application containing 60% ASMDAL. The minimum value of 13.78, on the other hand, was determined when using irrigation water at 20% ASMDAL and 40% ASMDAL (Table 4). These results were consistent with those of [9] who found the maximum number of tubers per plant treated with 60% ASMDAL.

Marketable tuber yield (t ha-^{1}): The result of this study showed that the effect of irrigation water application at different allowable soil moisture losses had a significant ($P<0.05$) impact on tuber yield of potatoes (Table 4). The highest marketable tuber yield (32.91 t ha-^{1}) was obtained from irrigation water application at 100% of the ASMDL, while the lowest marketable tuber yield (27.67 t ha-^{1}) was obtained from treatment by irrigation water application at 20%. by ASMDL. However, no significant difference in marketable tuber yield was observed between irrigation water application at 60% of the ASMDL and irrigation water application at 100% of the ASMDL (FAO recommended depletion limit). The present finding is consistent with the results of [16] who reported that the highest marketable yield from irrigation water application was at 100% of the ASMDL (FAO Recommended Soil Moisture Depletion Value).

Table 4. *Effect Optimal Irrigation using soil moisture depletion on Plant height, tuber weight, number of tuber per plant, marketable tuber yield, unmarketable tuber yield and Water productivity of potato.*

Treatments	PH (cm)	TW (g)	NTPP	MTY (t/ha)	UMTY (t/ha)	WUE (Kg m^{-3})
ASMDL 1	73.02	143.0	13.78^{c}	27.67^{c}	2.754	7.214^{c}
ASMDL 2	68.10	129.2	13.78^{c}	28.04^{bc}	2.959	7.310^{bc}
ASMDL 3	70.93	154.3	20.07^{a}	31.45^{ab}	3.107	8.199^{ab}
ASMDL 4	70.20	138.0	18.06^{b}	30.37^{abc}	2.033	7.918^{abc}
ASMDL 5* (Control)	73.73	164.2	18.72^{ab}	32.91^{a}	2.876	8.579^{a}
LSD (5%)	6.68	31.90	1.69	3.53	1.07	0.921
CV (%)	7.8	18.3	8.4	9.8	32.6	9.8

Where; PH: plant height, TW: tuber weight, NTPP: number of tuber per plant, MTY: marketable tuber yield, UMTY: unmarketable tuber yield, CV: coefficient of variation and WUE: water use efficiency

3.4. Effect of Soil Moisture Depletion Levels on Water Productivity

The effect of different irrigation water application The level of water productivity of potatoes under furrow irrigation showed a significant ($p<0.05$) impact on the water productivity of potatoes (Table 4). The maximum water productivity (8.579 kg/m^3) was achieved at 100% ASMDL. On the other hand, the lowest water productivity (7.214 kg/m^3) of the potato yield was obtained at 20% ASMDL. The soil-water-plant relationship was better in low-watered systems than in high-watered systems, which could contribute to higher yields and thus higher water productivity. The lower water productivity could be due to increased irrigation depth, much of which was lost through deep soil infiltration. The trend in water productivity in this experiment agrees with the findings [17] who reported that the lower the amount of irrigation water received, the higher the water productivity attained for drier plant biomass and berry yields. Similarly, result was reported that field grown beans achieved a higher WP with the lowest level of irrigation [11].

4. Conclusions and Recommendations

The application of the desired amount of irrigation water with the appropriate watering interval has a substantial impact on the potato yield. This result revealed that reducing the allowable soil moisture loss than recommended by the FAO had reduced both yield and water use efficiency. Based on this result, there was a significant difference between the treatments in terms of marketable tuber yield, number of tubers per plant and potato water productivity. Based on the obtained results of the effect of different irrigation schedules, the highest marketable tuber yield was obtained with the treatment of 100% ASMD (FAO recommended ASMDL), with no significant difference with the treatment of 80% ASMDL and 60% ASMDL, while the lowest marketable tuber yield was obtained The yield was obtained from 20% ASMDL. The higher water productivity of potatoes was also achieved with 100% ASMD, which is statistically similar to treatment with 60% ASMDL. Based on the present findings, the use of the ASMDL recommended by the FAo for potato cultivation in the study area and in similar agro ecologies is therefore recommended. Therefore, further investigation and verification work under different climatic conditions is recommended.

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