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Irrigation and Nitrogen Requirements of Wheat under Shallow Water Table Conditions of Asmara, Eritrea

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Abstract

Wheat (*Triticum astivum* L.) is traditionally rainfed in Eritrea. Yields are low because of poor soil management and low water and nutrient inputs. A field experiment was conducted in Akria farm, located in the outskirts of Asmara. The soil was clay loam associated with non-saline shallow water tables fluctuating from 0.4 to 1.2 m depths during the crop season. Wheat variety Wedel Nile was planted in split plot design with four levels of supplementary irrigations (SI) viz. I_1 (rainfed, 0 SI), I_2 (1/3 of full SI), I_3 (2/3 of full SI), and I_4 (full SI) in main plots and three levels of nitrogen viz. N_1 (18 kg N ha^{-1}), N_2 (50 kg N ha^{-1}), and N_3 (100 kg N ha^{-1}) as sub-plots in three replications. Full SI refers to amount of water necessary to replenish soil moisture deficit in the root zone from field capacity to 50% depletion of the available soil moisture. Groundwater table was constant around 0.4 m depth for 32 days from planting and declined slowly thereafter. Wetness around 0.3 m depth was thus near field capacity until second week of December and reduced thereafter with declining water table. Average soil moisture depletion was 94 mm under rainfed and 64 mm under full irrigation. No symptoms of wilting were observed in any of the treatments due to shallow water tables. Upward flux from the water table was 4.6 $mm \cdot d^{-1}$ until 30 days from planting, which declined to 0.2 $mm \cdot d^{-1}$ when the water table declined below 0.9 m depth. Optimum yield of wheat (5603 $kg \cdot ha^{-1}$) was obtained by application of 58 mm irrigation (I_3) and 100 $kg \cdot ha^{-1}$ nitrogen (N_3). Total water use for optimum yield of wheat was 382 mm and water use efficiency was 14.7 $kg \cdot ha^{-1} \cdot mm^{-1}$. Contribution from water table to the evapotranspiration requirements of wheat was highest (61%) under rainfed (I_1) and lowest (52%) under full SI (I_4).

Keywords

Evapotranspiration, Nitrogen, Supplementary Irrigation, Water Table Contribution, Water Table, Wheat

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1. Introduction

Wheat (*Triticum astivum* L.) in Eritrea is planted on highlands under rainfed conditions. Average yields range from 0.12 to 0.75 t·ha^{-1} due to poor soil management and low water and nutrient inputs [1] [2]. The crop is traditionally planted during rainy season on the existing undulating land slopes without adoption of any soil and water conservation measures. The crop is severely stressed during flowering onwards at which supplementary irrigations can significantly change yield scenario [2]-[4]. Efforts are being made in Eritrea to identify water resources and popularize soil and water management practices necessary to obtain sustainable high yields. Observations have shown that groundwater level in some parts of Asmara region is shallow and used for irrigating vegetable crops. Downstream side of the dams, low permeable black soils adjoining Asmara city, valley lands and depressions having limited drainage outlets are often associated with shallow water tables fluctuating from shallower than 0.5 to 1.5 m from the surface. However, no efforts have been made to quantify the potential of shallow water tables as source of sub-irrigation directly into the crop root zone. Although rainfall is low from September 10, other climatic requirements are optimum for wheat cultivation on highlands including Asmara region throughout the year.

Water and nutrient availability are major limiting factors of wheat production in the world [5]. Depending upon climate, length of growing period, soil and irrigation supplies wheat may require about 400 to 650 mm water for optimum yields [6]-[8]. Kahlown *et al*. [8] observed 650 mm evapotranspiration (ET) of wheat over the water table (WT) at 0.5 m depth, which reduced to 470 mm when the WT was at 1.5 m depth. Tripathi and Mishra [7] reported that both depths to the WT and soil texture affect wheat yields and ET. Wheat yields were 3850 kg·ha^{-1} and ET 430 mm over the WT fluctuating from 0.4 to 0.8 m depth in clay loam. However, yields increased to 5250 kg·ha^{-1} and ET reduced to 410 mm over the WT fluctuating from 2.36 to 2.48 m depth in loam. Uptake of nitrogen by wheat and yield responses changes significantly with soil moisture availability and time and amount of irrigation [3] [9]-[11]. Oweis *et al*. [3] reported that even 1/3 of full irrigation may increase wheat yields significantly but 2/3 of the full irrigation was optimum for near potential yields. Yang *et al*. [12] saved 99.5 mm irrigation through adoption of deficit irrigation. Sun *et al*. [13] observed that only 300 mm irrigation was necessary in northern China Plain for optimum yields. Wheat required irrigation only at crown-root initiation (CRI) stage in clay loam over the WT from 0.4 to 0.8 m depth and at CRI and flowering stages in silty clay loam over the WT from 0.66 to 1.4 m depth for optimum yields [14]. Kahlown *et al*. [8] also showed that wheat required 75 mm irrigation for optimum yields over the WT at 1 m depth. Chaudhary *et al.* [15] observed that irrigation amounts increased from 80 to 345 mm as WT receded from 0.5 to 1.5 m depth. Wheat growth was optimum over the WT fluctuating from 0.6 to 0.8 m depth in sandy loam to silty loams and in clay over the WT from 0.8 to 1 m depth [6]. About 70% of the total ET of wheat was met from the WT at 0.60 m depth [15] but it may exceed 90% from the WT at 0.5 m depth [8]. Maximum wheat yield was 5.5 t·ha^{-1} over 1.5 m WT, which reduced to 3 t·ha^{-1} over 0.5 m WT, perhaps due to reduced aeration in the root zone. Kahlown *et al*. [8] suggested that water tables shallower than 1.5 m may be detrimental to growth of deep rooted crops.

Nitrogen availability and use by wheat crop varies greatly with tillage and soil water availability [16] [17]. Net mineralization during the growing season was 71 kg N ha^{-1} under no tillage and 21 kg N ha^{-1} under the conventional tillage [17]. Response of wheat to fertilizer N in Mediterranean climates was optimum at 50 kg N ha^{-1} under rainfed and 100 kg N ha^{-1} under irrigated conditions [2]. Maximum water use efficiency under deficit irrigation was achieved at 60 kg N ha^{-1} combined with 1/3 of full supplementary irrigation [4]. Wheat yield was highest at 140 kg N ha^{-1} under well-watered conditions but only 70 kg N ha^{-1} was necessary with about 52% yield loss when no irrigation was given at tillering and jointing stages [18]. Oweis *et al.*, [3] reported that supplementary irrigations significantly increased fertilizer use efficiency. Apparent fertilizer N recovery was above 25% for rainfed and 45% for irrigated wheat. Application of 150 kg N ha^{-1} reduced wheat yields under rainfed conditions. Wheat yields were limited by water availability with increasing N applications. Application of 1/3 of full irrigation with 100 and 150 kg N ha^{-1} doubled wheat yield from that under rainfed [3]. Efficient N fertilizer management is critical for economic production of wheat and long-term protection of environmental quality [19]. Since no such studies were reported from Eritrea, experiments were conducted to optimize irrigation and nitrogen requirements of wheat under natural shallow water table conditions of Akria farm, Asmara.

2. Experimental Details

2.1. Soil

Experimental field was clay loam (21% sand, 42% silt and 37% clay) in Akria farm located at 15˚21'41.6"N and

38˚56'33.9"E at an altitude of 2232 m above mean sea level. The farmland is surrounded by about 36.5 ha hilly terrain that drains into 6 ha cultivated valley land. There are three micro dams located on the hill on 3 sides. Climate of the area is semiarid with 15-year average annual rainfall of 459 mm. Rainfall in 2006 was 550 mm, of which 88.8 mm was during the crop season from October to February (**Figure 1**). Highest mean monthly temperature occurred in June (25˚C) and lowest in January (4.6˚C). Relative humidity was lowest in March (43.6%) and highest (82.6%) in August. Evaporation was maximum (364 mm) in May and minimum (101 mm) in July.

Average bulk density of surface soil was 1.2 $Mg \cdot m^{-3}$ in 0 - 0.4 m layer and 1.3 $Mg \cdot m^{-3}$ in the layer below. Average saturated hydraulic conductivity was 6 $mm \cdot d^{-1}$ in 0 - 0.4 m layer and 8.5 $mm \cdot d^{-1}$ in lower layers. Field capacity moisture was 0.4 $m^3 \cdot m^{-3}$ and wilting point 0.26 $m^3 \cdot m^{-3}$. Electrical conductivity of soil was 0.23 $dS \cdot m^{-1}$ and pH (1:5) was 8. Exchangeable Ca, Mg, K and Na were 37.7, 5, 1.48, and 1.34 $cmol \cdot kg^{-1}$, respectively. Extractable P was 228 $mg \cdot kg^{-1}$ and N 0.23% and organic matter 4.4%. The soil was calcareous dominated by sediments received from the surrounding hilly terrain over the years and has been under cultivation for more than 10 decades. The field was associated with shallow water tables fluctuating from 0.4 to 1.2 m depths from surface during the crop season. The well water was non saline (0.65 $dS \cdot m^{-1}$).

2.2. Treatments and Measurements

Wheat variety Wedel Nile was planted in split plot design on October 04, 2006 at a seed rate of 100 $kg \cdot ha^{-1}$, in rows 0.2 m apart. The treatments were 4 levels of supplementary irrigations (SI) viz., I_1 (rainfed, 0 SI), I_2 (1/3 of full SI), I_3 (2/3 of full SI), and I_4 (full SI) in main plots and 3 levels of nitrogen viz. N_1 (18 kg N ha^{-1}), N_2 (50 kg N ha^{-1}) and N_3 (100 kg N ha^{-1}) in subplots in 3 replications. Area of each subplot was 4 m × 3 m. Nitrogen was applied through urea and phosphorous through DAP. One-third N was applied as basal dose along with DAP and the remaining 2/3 N was topdressed in 2 splits on 21 and 45 days from planting.

Irrigation in I_4 (full SI) was 50% depletion of the available water holding capacity of the root zone [20]. Other treatments were irrigated along with I_4 as scheduled. The available water holding capacity was determined from the moisture content at field capacity (0.03 MPa) and wilting point (1.5 MPa) of each horizon. The soil water content was determined weekly by gravimetric sampling at 0.15 m depth interval down to 0.1 m above the water table in I_4 and only at sowing and harvesting in the other treatments. Soil water retention was also determined at 0.005, 0.01, 0.03, 0.06, and 0.1 MPa pressures on pressure plate apparatus using undisturbed samples collected in 0.02 m long and 0.05 m diameter metal cores from each horizon. Saturated hydraulic conductivity, K, of the soil of each horizon was determined by constant head permeameter using undisturbed soil samples in metal cores of 50 mm length and diameter. Depth to the water table was measured daily through 5 piezometers installed in the field. Grain yield was reported at 14% seed moisture.

2.3. Water Use

Evapotranspiration during n days (ETn, mm) was determined using the relation:

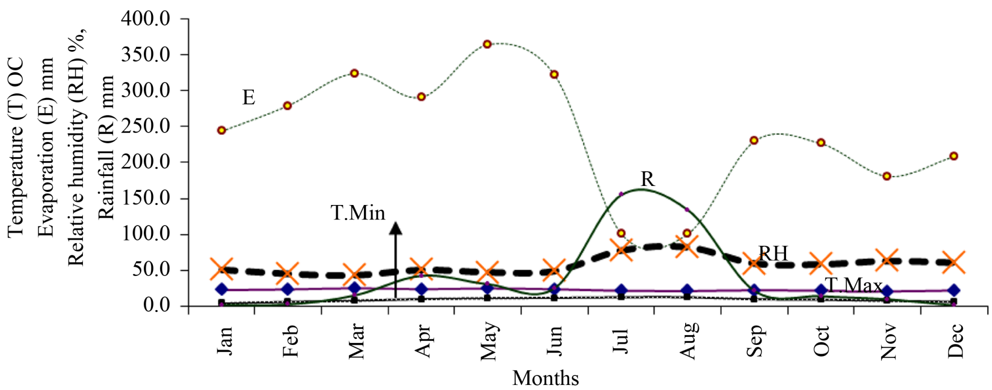

Figure 1. Mean monthly minimum temperature (T_{min}), maximum temperature (T_{max}), relative humidity (RH), and monthly rainfall (R), and evaporation (E) at Asmara.

$$\mathrm{ET_n = R_n + I_n + W_n - D_n \pm \Delta S_n} \quad (1)$$

where R_n is rainfall in (mm), In is irrigation water (mm), W_n is water table contribution (mm), D_n is drainage (mm), and ΔS_n change in soil water storage or loss in n days (mm). Since amount of rainfall was small and plots were level, runoff was zero. ΔS_n and D_n were calculated from the measured water contents in the profile as described by Tripathi and Mishra [7].

$$\mathrm{D_n = 0 \text{ for } S_n < S_p; \text{ and } = S_n - S_p \text{ for } S_n > S_p} \quad (2)$$

where S_n is soil moisture storage on nth day and Sp is potential storage capacity of soil considered as field capacity. Water table contribution into the root zone was calculated daily from suction measurements by tensiometer installed at 0.1 m above the water table using the relationship:

$$q = -K(\psi)\frac{\mathrm{d}H}{\mathrm{d}Z} \quad (3)$$

where q is ground water flux into the root zone, mm·day^{-1}, $K(\psi)$ is hydraulic conductivity, mm·d^{-1}, of soil at average soil suction (ψ, cm) between the tensiometer depth and the water table, dH/dZ is hydraulic gradient across the water table and tensiometer depth. The $K(\psi)$ was calculated using pore size distribution model [21] as:

$$K(\psi) = MF\left(\frac{\rho_w g\,\theta\, r^2}{8\eta}\right) = 0.3\left(\frac{\rho_w g\,\theta\, r^2}{8\eta}\right) \quad (4)$$

where MF is matching factor, ρ_w is density of water (cm^3·cm^{-3}), θ is volumetric water content (cm^3·cm^{-3}), η is viscosity of water (g·cm·s^{-1}), r is effective pore radius (cm). The MF was determined as ratio of the measured to calculated K at saturation. As determined, the calculated K was 25.3 mm·d^{-1} at 0.02 bar suction and average measured K at saturation was 8.2 mm·d^{-1}. Therefore, MF was obtained as 0.3.

3. Results and Discussion

3.1. Groundwater Table Fluctuation

Water table in 2006 fluctuated from 0.4 m depth at sowing to 1.2 m depth at harvesting (**Figure 2**). Each value in the figure represents an average of 5 piezometer readings. Water table remained constant around 0.4 m depth for 32 days from planting and declined thereafter at an average rate of 0.007 m per day until the crop harvesting. The water table showed no fluctuation in response to rainfall during the initial 32 days period but thereafter it showed a temporary rise following irrigations and rainfall. The initial constant position water table for the first 32 days indicates that crop evapotranspiration (ET) was supplemented by inflow of groundwater into the field from the adjoining 36.5 ha hilly terrain.

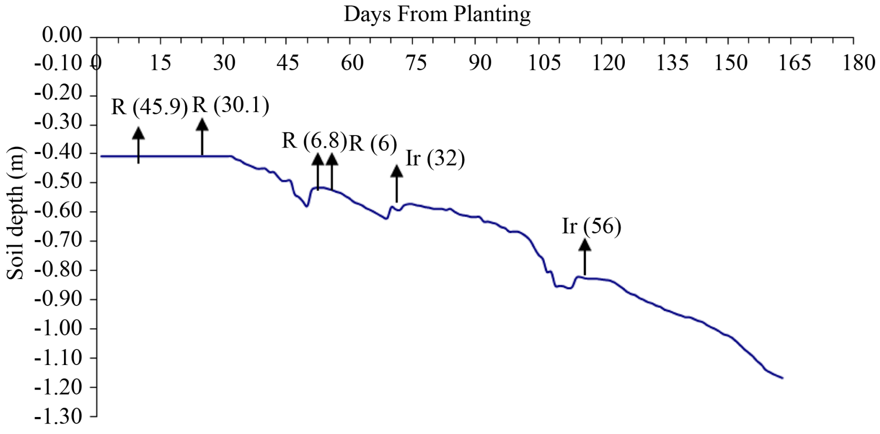

Figure 2. Water table fluctuation during the crop season. Arrows indicate date of rainfall (R), or irrigation (Ir) and numbers in parenthesis indicate amount of R or Ir in mm.

3.2. Soil Moisture Distribution

Soil moisture content (SMC) in the plots was almost uniform at planting (Figure 3). At 0.15 m depth, the SMC was near field capacity (0.391 $m^3 \cdot m^{-3}$) but it was above field capacity (0.40 to 0.412 $m^3 \cdot m^{-3}$) below 0.3 m depth. Greater wetness below 0.3 m depth indicates positive accretion as seepage in the experimental field.

Soil moisture depletion from 0 - 0.3 m layer was not appreciable (Figure 4) until 27 days from planting

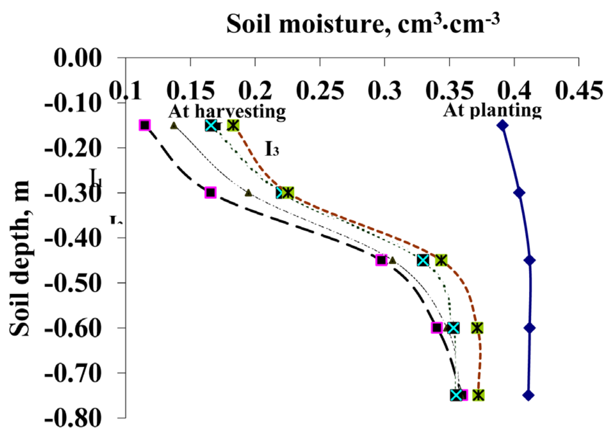

Figure 3. Soil moisture content at planting and harvesting in irrigation treatments.

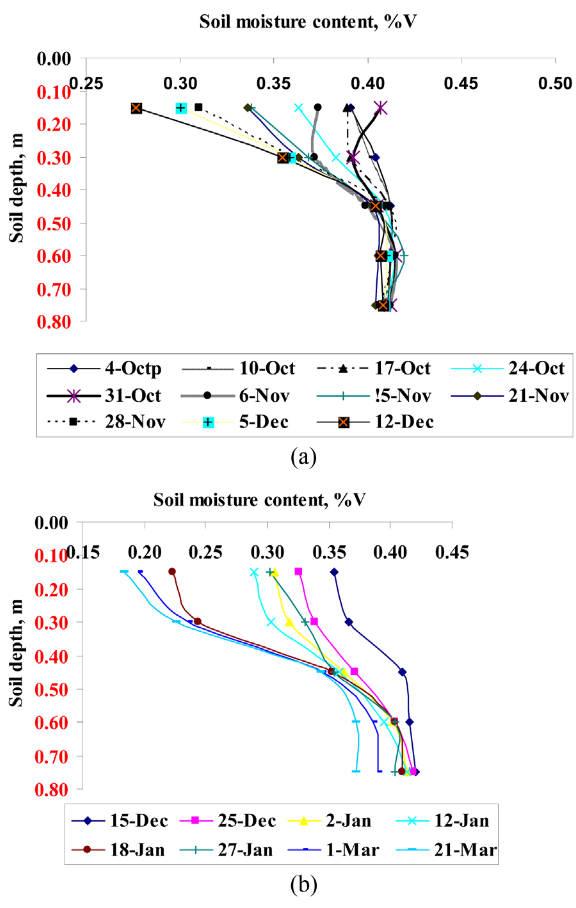

Figure 4. Weekly soil moisture distribution in full SI (I_4) treatment during (a) Oct 4 to Dec 12, 2006 and (b) Dec 15, 2006 to March, 2007.

(DFP). The soil moisture started depleting from 33 DFP till the first irrigation (71 DFP). A total of 25.2 mm of water was depleted from the root zone (0 - 0.3 m) of the profile. On 71 DFP irrigation was given in the full SI (I_4) treatment to refill the deficit. Other treatments were irrigated on the same date. After first irrigation, SMC depleted continuously and a total of 45 mm water was depleted in 41 days from the root zone (0 - 0.45 m) of the full irrigation treatment (I_4).

In I_1, I_2, and I_3, the SMC in 0 - 0.3 m layer depleted well below wilting point but was within the available range below 0.3 m depth. A total of 94 mm, 85 mm, 73 mm, and 62 mm of soil moisture depleted from I_1, I_2, I_3, and I_4 treatments, respectively. Total moisture content at harvesting in the 0 - 0.45 m layer of I_4, I_3 and I_2 was 1.7 mm, 1.4 mm and 0.6 mm higher than in the rainfed (**Figure 3**). There was no appreciable difference in moisture content among the treatments below 0.45 m depth. The crop did not show any symptoms of wilting perhaps due to proximity of roots to the water table (**Figure 5**).

3.3. Groundwater Flux from the Water Table

Flux from the water table into the crop root zone was higher in the beginning of the crop season and declined with water table receding downwards (**Figure 6**). Average flux during the first 30 days was 4.6 mm·d^{-1}, which reduced to 2, 0.5 and 0.2 mm·d^{-1} during 30 - 60, 60 - 90, and 90-harvesting date, respectively, with declining water table. Flux from the water table was sharply reduced following rainfall and irrigations. Upward flux declined sharply when water table receded from 0.55 - 0.65 m but the reduction slowed down with further decline in water table to 1.05 m.

3.4. Grain Yield and Water Use

Wheat yields were significantly affected by irrigation and nitrogen (**Table 1**). Mean yields due to irrigations

Figure 5. Wheat crop at grain development stage.

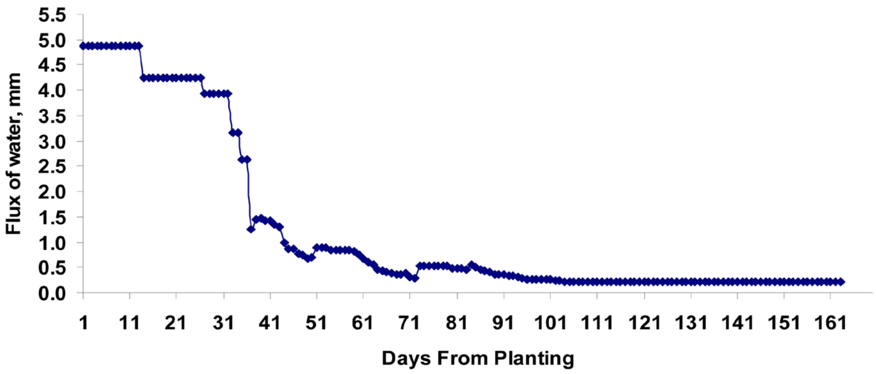

Figure 6. Water flux from the water table (mm·d^{-1}).

Table 1. Grain yield at different irrigation and nitrogen levels.

Irrigation Levels	Grain yield, kg·ha^{-1}, at nitrogen levels				Mean depletion, mm	Mean water use (mm)
	N_1	N_2	N_3	Mean		
I_1	3171	3614	3457	3414	94	345
I_2	3624	4288	4600	4171	85	366
I_3	4286	4684	5603	4858	74	382
I_4	4410	5005	5802	5072	62	401
Mean	3873	4398	4866			
Factors	I	N	I × N			
LSD (0.05)	407	389	711			

I_1 = Rainfed; I_2 =1/3 of full irrigation; I_3 =2/3 of full irrigation; I_4 = Full irrigation; N_1 =18 kg N ha^{-1}; N_2 = 50 kg N ha^{-1}; N_3 = 100 kg N ha^{-1}.

were significantly high (4858 kg·ha^{-1}) in I_3 (75% of full irrigation) and that due to nitrogen were significantly high (4866 kg·ha^{-1}) in N_3. Interaction effects showed that yields were significantly high in I_3N_3 (5603 kg·ha^{-1}) and at par with that in I_4N_3. These yields are as against <0.75 t·ha^{-1} harvested by farmers from the June planted (rainy season) wheat [1]. Water use for optimum yield (5603 kg·ha^{-1}) in I_3N_3 was 382 mm. Amount of irrigation applied in I_3 was 58 mm and that in I_4 and I_2 was 88 mm and 30 mm, respectively. The water table contribution was 61%, 57%, 55%, and 52% of the ET requirements of wheat under rainfed (I_1), 1/3 full SI (I_2), 2/3 full SI (I_3), and full SI (I_4), respectively. Soil moisture depletion was highest in I_1 (94 mm) and lowest in (I_4). Results show that for efficient utilization of water resources, scheduling of irrigations should be based on depth to the water table, soil moisture depletion, rainfall and contributions from the water table.

4. Conclusions

1) It is possible to produce off season wheat exceeding 5.6 t·ha^{-1} by <60 mm irrigation and application of 100 kg N ha^{-1} in the soils associated with water table fluctuating from 0.4 to 1.2 m depth from surface.

2) Groundwater levels in some parts of Asmara region including Akriya farm are high enough to serve as a source of supplementary irrigation to crops.

3) Although rainfall is low after September, yet other climatic requirements are optimum for wheat cultivation throughout the year in highlands of Asmara region.

4) Irrigation requirement of wheat is much lesser than used by farmers to produce vegetable crops.

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