Soil-Water Depletion Changes and Water Requirement Satisfaction Index of Major Crops Grown on Bella-Weleh Catchment, Sekota

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Abstract

Water requirement satisfaction index (WRSI) is 'an indicator of crop performance based on the availability of water to the crop during a growing season' that calculated using a water stress index, which helps to determine whether a given crop has sufficient water to achieve its potential yield throughout the growing season. The objective of the study was to quantify the soil-water depletion of barley, wheat and teff crops, evaluating the crops' performance across the catchment and mapping the catchment based on the WRSI of each crop. The catchment was classified on three strata based on elevation, soil depth and soil texture and in each strata barley, teff and wheat farm lands were selected. Gravimetric moisture content was collected under each crop for soil moisture status in a temporal and spatial manner. The probability of dry (P_{80}), normal (P_{50}) and wet (P_{20}) season occurrence in the area was calculated from the logarithmic regression and the values were 403.24 mm, 515.37 mm, and 733.98 mm.

Overall, barely, followed by wheat, had better WRSI as compared to teff. The overall maximum crop evapo-transpiration of barley was 227.9 mm, 231.6 mm and 227.9 mm in the upper, middle and lower sub-catchment farmlands, respectively, whereas the corresponding actual evapo-transpiration was 195.1 mm, 203.3 mm and 208.2 mm. Similarly, the seasonal maximum evapo-transpiration of wheat was 302.4 mm, 305.2 mm and 306 mm in the upper, middle and lower sub-catchment farmlands, respectively, whereas the corresponding actual evapo-transpiration values were 179.7 mm, 197.5 mm and 226.8 mm. The seasonal maximum and actual evapo-transpiration of teff was 336.2 mm and 139.5 mm, 342.0 mm and 159.3 mm, 344.9 mm and 201.0 mm in the upper, middle and lower sub-catchments, respectively. The yield difference among the farmlands was minimum for barely (0.05 t/ha), intermediate for wheat (0.19 t/ha) and high for teff (0.43 t/ha). In most of the measured parameters, the upper sub-catchment was inferior to the lower sub-catchment, clearly showing the differences in resource base among the sub-catchments. Supplemental irrigation and/or water conservation structures should be practiced during the rainfed cropping system in order to get the potential yield of teff and wheat in the catchment and similar agro-climatic areas, especially in sandy-to-sandy clay loam texture soils.

Key words: Water requirement satisfaction index, Moisture deficit, Catchment

Introduction

Understanding the principles of water movement in the soil profile and continuous evaluation of the storage and balance of soil water are important for efficient soil and water management, crop selection, irrigation scheduling and runoff prediction. Water sfrvjsfnfou! tbujtgbdujpo! joefy!)XSTJ! jt! 'bo! joejdbups! pg! dspq! qfsgpsnbodf! cbtfe! po! uif! bwbjrbcjmjuz! pg! xbufs! up! uif! dspq! evsjoh! b! hspxjoh! tfbtpo!)Tfobz! boe! Wfsejo! 3113 /! WRSI is calculated using a water stress index calculation scheme that helps determining whether an agricultural season has performed well and a given crop has sufficient water to achieve potential yield (Hoefsloot, 2004). WRSI indicates the extent to which the water requirement of a given crop has been satisfied in a cumulative way at any growth stage (Mukhala, 2002). FAO studies (Doorenbos and Pruitt, 1977) have shown that WRSI can be meaningfully related to crop production in semi-arid regions, using a linear-yield reduction function specific to a crop. Senay and Verdin (2001) and Abate (1994) reported that when the index falling below 50%, there is a total crop failure, i.e., it is unsuitable for crop production during that particular season for North Western Ethiopia. The WRSI from 51-75% are considered as moderately suitable, while WRSI values larger than 75% indicate adequately available water for a sorghum grown at a given location during that particular season.

Similarly, Diga (2005) reported that WRSI from 100% to 75% resulted in a 49.7% yield reduction in case of Miesso, 40.8% in case of Melkassa and 24.3% in case of Arsi Negele. Further, when WRSI was reduced down to 50%, there was a total crop failure in the case of Miesso and Melkassa, while the reduction was 48.6% for the Arsi Negele. Similar results were found when WRSI was varied across other input level combinations.

Doorenbos and Pruit (1977) reported that wheat should be irrigated when 55% of the plant available water is depleted in the root zone. They suggested that when crop water use is less than 0.10 inches/day this value should be increased by 30% (to 72% allowable depletion) and when crop water use is greater than 0.30 inches/day this value should be decreased by 30% (to 38% allowable depletion). During ripening, the maximum allowable depletion of plant available water is 90%. The optimum soil water depletion level according to grain yield was 35% for each variety and averaged over varieties. The lowest yield was obtained at 65 and 80% depletion averaged over varieties, and yield at 50% depletion was intermediate.

Materials and Methods

Description of the Study Area

The study was undertaken in Bella-Weleh catchment, which is found in Sekota wereda in the northeast of the Waghimra zone at about 725 km north of Addis Ababa. The catchment extends from 12°38 21/9 O! up! 23°46 42/3 O! boe! 49°6: 24/3 F! up! 39°15 41 F! boe! i bt! bmjuvef! ui bu sbohft! cfux ffo! 2:87-3600 m asl. The catchment is characterized by a unimodal rainfall pattern, which extends from late June to late August or early September, where crops are cultivated in summer season. Mean annual rainfall varies from 333 to 1016 mm. The mean minimum and maximum annual temperatures are 8 and 21°C, respectively. The major agro-ecological characteristics of this catchment are hot and warm sub-moist to semiarid lowland with tepid to cool sub-moist environment in the Bella Mountain that skies up to 3600 m asl.

The general slope range on which the farmlands occur varies between 0 and 8%, but could be normally found on 0-25 % slope range. The soil type is predominantly alluvial deposits, well drained, light to dark brown in color, and with very shallow-to-shallow soil depth, sandy to sandy clay loam in texture, highly eroded and continuously cultivated, with rock outcrops of basalt and sandstone (Akundabweni, 1984).

For this study, the catchment was divided into four categories as mountainous, upper, middle and lower sub-catchments/strata. The three sub-catchments of the cultivable area were delineated based on selected criteria viz. elevation, soil color, soil depth, soil texture and slope. From each of the selected sub-catchments/strata, three farmlands of *teff*, wheat and barley were selected, making a total of nine farmlands. The farmers themselves managed the selected farmlands. The individual crop cultivars selected, ’Bx sbhfct ! pg cbsfm ! ’ fcfobj ! pg x i fbu boe! ’Cvojf ! pg *teff*, were the locally grown ones. The mountainous part of the catchment shares around 45% of the total area followed by the lower sub-catchment (29%), the middle sub-catchment (13%) and the least is the upper sub-catchment (12.5%).

Soil Sampling and Analysis

From the selected farmlands, disturbed (by using auger) and undisturbed (using core sampler) soil samples were collected at four points in each farmland by using traverse sampling technique and composited to make one composite sample per farmland. The soil properties that were determined and/or analyzed included particle size distribution, bulk density, water retention characteristics curve, pH, OM, exchangeable cations (Na^+, K^+, Ca^{++}, Mg^{++}), CEC, EC, total nitrogen and available phosphorus.

Quantification of WRSI and Soil Water Depletion

The decadal water requirement satisfaction index was estimated using the following relationships

$$WRSI = \frac{\sum ET_a}{\sum ET_c} \quad WRSI = \left(\frac{\sum ET_a}{\sum ET_C}\right) \times 100\%$$

Where:

WRSI = decadal water requirement satisfaction index (%),

ET_a= decadal actual evapo-transpiration (mm), and

ET_c= decadal potential crop evapo-transpiration

Since there was no irrigation and the ground water table is too deep to affect the root zone moisture, the decadal actual crop evapo-transpiration was calculated using the water balance equation:

$$ET_a = P + \Delta SW - (R + DP)$$

Where:

P = total precipitation (mm), recorded using rain gauge

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R = runoff losses (mm), and

DP = deep percolation losses (mm).

Ui f! efdbebrh tpjrh x bufs! dpouSjccvujpo!) TX ! x bt! ftujn bufe! gspn ! ui f! gpmpx joh! relationships:

$$\Delta SW = \sum_{i=1}^{n} \frac{(\Theta_i - \Theta_{i-1})}{100} \times D_i$$

Where:

$_i$ = soil water content at the time of end of the decade for the ith layer (% mass),

$_{i-1}$ = soil water content at the time of start of the decade for the ith layer (%),

D $_i$= depth of the ith layer (mm).

During wet periods when either the rainfall exceeds evapo-transpiration (i.e., P > ET_c) or the moisture content is above field capacity, the moisture storage, S_t, was determined gspn ! ui f! bee juipo! pg ui f! qsfwjpvt! e bz t! n pjtuvsf ! T_t u(mm), to the difference between precipitation and evapo-transpiration, during the time step. Conversely, when evapo-transpiration exceeds rainfall (i.e., P < ET_c) and the moisture content of the soil is at or below field capacity (dry conditions), ET_a (mm), decreases linearly from the potential rate at field capacity to zero at the wilting point (Steenhuis and van der Molen, 1986). Under such circumstances, the ETa was estimated using the following relationship:

$$ET_a = ET_c \left(\frac{S_t}{AWC} \right)$$

However, from late August onwards, runoff (R) and deep percolation losses (DP) were also assumed to be negligible since this time corresponds to the end of the rainy season. The crop ET_c was calculated from the ET_o and K_c using CROPWAT model (FAO, 1998). The CROPWAT 8.0 for windows software was used to calculate ET_o by using the FAO modified Penman-Montheith equation from monthly average wind speed, sunshine hours, min and max temperatures and humidity. The individual crop coefficients were obtained from LEAP 2.10 software for Ethiopia (Hoofslot, 2009) as indicated in Table 1.

Table 1: Crop coefficient with fraction of crop cycle of barley, wheat and teff (adapted from LEAP 2.10 software for Ethiopia (Hoofslot, 2009)

Crop	Initial		Vegetative		Flowering		Ripening	
	Fraction of cycle end	Kc	Fraction of cycle end	Kc	Fraction of cycle end	Kc	Fraction of cycle end	Kc
Barley	0.16	0.3	0.41	0.3	0.84	1.2	1.0	0.25
Wheat	0.16	0.3	0.42	0.3	0.84	1.2	1.0	0.25
Teff	0.16	0.3	0.42	0.3	0.82	1.2	1.0	0.25

The soil moisture depletion was quantified using the following relationship:

$$SMD = (\theta_{FC} - \theta_{C}) \times D$$

Where:

SMD = soil moisture depletion (mm),

θ_{FC} = volumetric water content (vol/vol),

θ_{C} = current or measured water content (vol/vol), and

D = depth of the root zone considered (mm).

The crop moisture deficit (MD), which descRibbes the intensity of the crop water stress, was estimated from the following assumptions:

$$MD = ET_c - ET_a \quad \text{if } ET_c > ET_a$$
$$MD = 0 \quad \text{if } ET_c = ET_a$$

The fraction of available water stored (soil water index) in the crop root zone at the end of a particular decade was then calculated as follows:

$$SWI = \left(\frac{SW_i}{WHC}\right) \times 100\% \; SWI = \frac{SW_i}{WHC} X100$$

Where:

SWI = soil water index (%),

SW_i = soil water content at the i^{th} decade (%), and

WHC = soil water holding capacity (%).

The index indicates the soil moisture status at the end of a particular decade and, hence, used to assess the crop water status in the next decade based on the available moisture in the soil.

Moisture and Meteorological Data Collection and Analysis

Temperature (daily max and min), wind speed (ms^{-1}), sunshine hours, and relative humidity (%) were extrapolated from Michew and Lalibela meteorological stations based on Bekele (2006) as:

$$\text{Sekota} = 0.682 \times \text{Michew} + 0.328 \times \text{Lalibela}$$

Six years (2004-2009) daily rainfall data was obtained from the catchment whereas the sfn bjo joh! 29! zf bst ! sbjogbmm ebub x fsf! fyusbqpmbufe! gspn ! N jdi fx ! boe! Mbmjcf mb! sbjogbmm data for calculation of rainfall probability. An estimate of the respective rainfall data was obtained by computing and plotting probabilities from the rainfall records based on the method stated in http://www.fao.org/nr/water/docs/CROPWAT8.0Example.pdf.

Soil moisture content was recorded in 10 days interval between July 5 and August 4 and in 5 days interval between August 5 and harvest of the respective crops. The gravimetric water content was determined as the ratio of weight loss after oven drying to oven dry weight of the sample. The gravimetric water content was then converted into volumetric water content by multiplying with the dry bulk density of the soils.

Results and Discussion

Climatic Characteristics

The long-term rainfall data analysis indicates that the rainfall is concentrated in the months of June, July and August. The normal (P_{50}), dry (P_{80}) and wet (P_{20}) seasons rainfall values estimated from the rainfall frequency curve, constructed using the 24 years rainfall record, were 403.24, 515.37 and 733.98 mm, respectively based on the proposed criteria of Elias and Castellví (2006) as reported by Ramos and Martínez-Casasnovas (2010). All the normal, dry and wet season rainfall values indicate that more than 87% of the total annual rainfall occurs during the months of June, July and August and decreases afterwards. This implies that, depending on the length of the crop cycle and the available water holding capacity of soils of the catchment, the probability that the crops may experience terminal moisture stress is high, and Tonietto and Carbonneau (2004) have reported similar implications.

The 2009/2010 cropping season total rainfall was 429 mm, which according to the rainfall values approaches the dry season characteristics. The majority of the rainfall that was recorded during this season was in July (206 mm) and in August (205 mm). The seasonal rainfall trend was also in consent with the long-term rainfall pattern. The decadal rainfall distribution shows that there was even a dry spell between the last week of July and first week of August. Further, the rainfall drops below half the reference evapo-transpiration towards the end of the first decade of September. Once again, the survival of the crops depends on the amount of soil moisture reserve stored during the humid months. Because effectiveness of rainfall depends not only on the quantity of rainfall, but also on the distribution (Hatibu et al., 2003).

Spatial Variability of the Soil Properties

The soils are of sandy loam in the upper sub-catchment, sandy clay loam in the middle sub-catchment and clay loam in the lower sub-catchment in texture according to the USDA soil textural classification. Across the sub-catchments, bulk density decreased from the upper-sub-catchment towards the lower sub-catchment. As a result, the highest bulk density values were recorded in the upper sub-catchment, which according to Murphy (1968) is rated as high. The relatively high bulk density values recorded in the upper sub-catchment might, in addition to the compaction caused by plowing, be due to the dominance of the sand fraction, which weighs more per unit volume compared to the silt and clay fractions.

The total available moisture followed the trends of water content at field capacity and permanent wilting point (Table 2). This clearly shows the considerable spatial difference in the available water holding capacity of the soils in the catchment and their suitability to successfully support or not support crop growth after cessation of rainfall. In addition, the upper sub-catchment has a very shallow soil depth, which resulted in total available moisture (TAM) that was approximately half of that held by the clay loam soils of the lower sub-catchment. The upper sub-catchment soils are, therefore, not effective for moisture storage for later use and crops grown on these sandy loam soils might face moisture stress during a dry spell when compared to the sandy clay loam and clay loam soils of the middle and lower sub-catchment, respectively. In general, the soils of the farmlands in all the sub-catchments have low fertility status although soils of the farmlands in upper sub-catchment had the lowest fertility status. The exchangeable sodium percentage (ESP) in all the soils was below 15% and rated as non-sodic according to Landon (1991).

Table 2: Selected physical properties of soils in Bella-Weleh catchment

Section	Profile depth (cm)	Particle size distribution (%)			Texture class	Bulk density (g/cm^3)	Total porosity (%)	Volumetric moisture content (%)			TAM (mm/m)
		Sand	Silt	Clay				FC	PWP	AWC	
USC	0-40	61.9	22.9	15.2	SL	1.63	38	16.24	8.23	8.01	79.54
	40-58	55.2	25.1	19.7	SL	1.66	37	14.58	6.75	7.83	
MSC	0-40	59.2	19.3	21.5	SCL	1.54	42	21.45	11.29	10.16	
	40-70	49.8	21.1	29.1	SCL	1.57	41	17.31	8.92	8.39	94.01
LSC	0-40	33.5	28.0	38.5	CL	1.35	49	31.83	17.01	14.82	
	40-85	33.1	25.2	41.7	CL	1.41	47	30.36	16.09	14.27	145.29

USC = Upper sub-catchment, MSC =Middle sub-catchment, LSC =Lower sub-catchment, SL = sandy loam, SCL = sandy clay loam, CL = clay loam

Moisture Deficit and Water Requirement Satisfaction Index

Barley farmlands

In all the farmlands, relatively low moisture deficit was recorded during the third decade of July (12-23 days after planting) and second decade of August (33-43 days after planting). These are the periods during which there was high rainfall and high soil water index. As a result, moisture deficit was not a problem at this stage of the crop. Furthermore, the moisture deficit increased to relatively high values towards the end of the crop cycle in all the farmlands except the middle sub-catchment farmlands, which showed a decreasing trend. This is because September was a month with limited rainfall and, therefore, the crop relies on the soil water reserve stored during the months of July and August. Towards the end of September, this reserve moisture must have been depleted and therefore high moisture deficit.

Some variations in water requirement satisfaction index were observed among the farmlands in the three sub-catchments although the seasonal trends were similar (Figure 1). This is due to the spatial variability of moisture stored during a growing period as a result of heterogeneous conditions of surface and bedrock topography and soil characteristics as suggested from Penna et al. (2009) findings. In general, the index in all the farmlands showed a decreasing trend towards the end of the crop cycle. In the upper sub-catchment, the index varied from 43.8% during the second decade of September (at harvest) to 99.2% during the second decade of July (12-23 days after planting). In the middle sub-catchment, it ranged from 46.7% at harvest to 99.4% during the second decade of July. Similarly, in the lower sub-catchment it varied from 63.4% during the first decade of July to 99.4% during the second decade of August (33-43 days after planting).

Considering seasonal averages of the crop cycle, the moisture deficit varied from 2 mm/decade in the lower sub-catchment field to 4 mm/decade in the upper sub-catchment field. Similarly, the mean seasonal water requirement satisfaction index of the barely farmlands ranged from 84% in the upper sub-catchment to 86% in the lower sub-dbudi n fou!Ui f tf!wbmf t!gbmhjo!ui f!sbohf!pg'tbujtgbdupsz !bt!qfs!ui f!XSTJ!sbujoh!pg Senay and Verdin (2002).

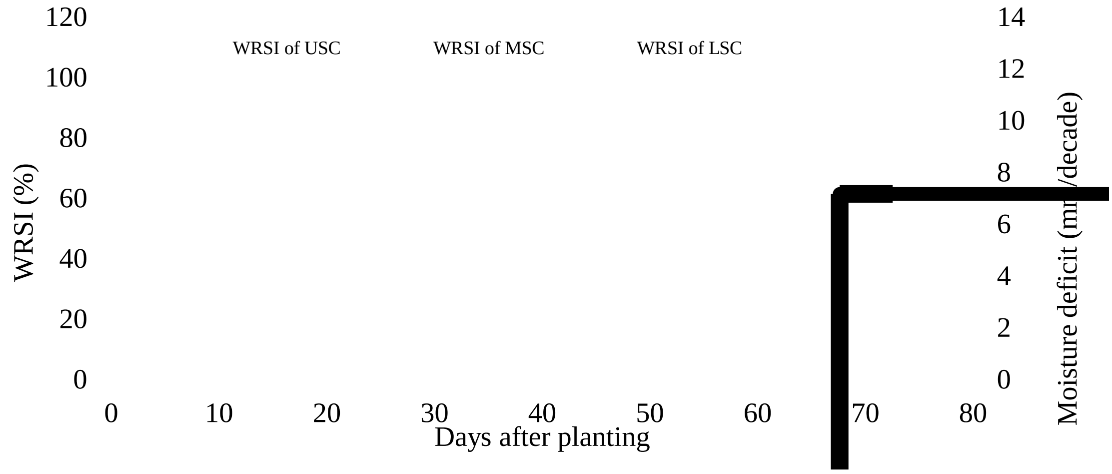

Figure 5: Seasonal variations of water requirement satisfaction index (WRSI) and moisture deficit (MD) of barely farmlands in Bella-Weleh catchment. USC = Upper sub-catchment, MSC =Middle sub-catchment, LSC =Lower sub-catchment

Wheat farmlands

In all the farmlands, the moisture deficit was the lowest during the second decade of July followed by the second decade of August. This was so because there was high rainfall during these decades and expectedly the soil was near saturation. Furthermore, the crop was at its early stage during the second decade of July (only 12 days after sowing) and therefore had low water requirement. On the other hand, the deficit was the highest in all the farmlands during the third decade of September (79 -90 days after planting). This was due to the low rainfall during the decade, no rainfall during the previous decade and then low soil moisture storage. It is also interesting to note that the moisture deficit showed three distinct patterns across the whole of the crop cycle. From 7 to 49 days after planting, there was generally low but irregular pattern of moisture deficit followed by a consistently sharp increase between 49 and 79 days after planting and a consistent decrease between 79 to 96 days after planting. The decrease in moisture deficit towards the end of the crop cycle regardless of low available soil moisture could be related to the low water requirement of the crop at this stage. Within the wheat farmland of the catchment, the average moisture deficit of the season varied from 12.26 mm/decade in the upper sub-catchment to 7.91 mm/decade in the lower sub-catchment.

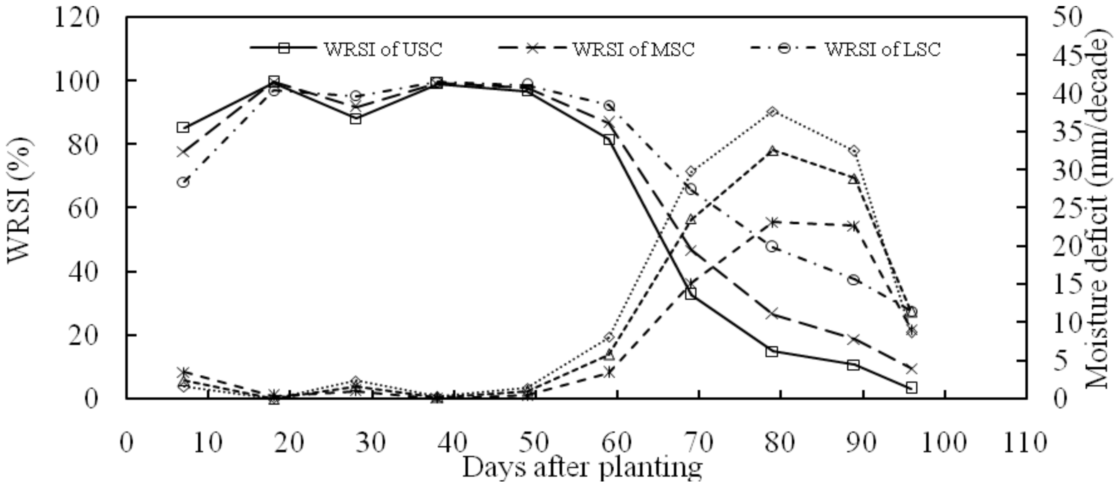

Figure 6: Seasonal variations of water requirement satisfaction index (WRSI) and moisture deficit (MD) of wheat farmlands in Bella-Weleh catchment. USC = Upper sub-catchment, MSC =Middle sub-catchment, LSC =Lower sub-catchment

The water requirement satisfaction indices of the wheat farmlands in the three sub-catchments showed irregular patterns between third decade of July and August (i.e., 7 and 49 days after planting). Between the third decade of August and harvest of the crop (i.e., 49 to 96 days after planting), however, the indices decreased consistently reaching the lowest value at harvest. In all

The average seasonal moisture deficit in the *teff* farmlands of the catchment varied between 20.9 mm/decade in the upper sub-catchment and 15.0 mm/decade in the lower sub-catchment. The average seasonal moisture deficit in the middle sub-catchment was 19.0 mm/decade almost equivalent to that of the upper sub-catchment.

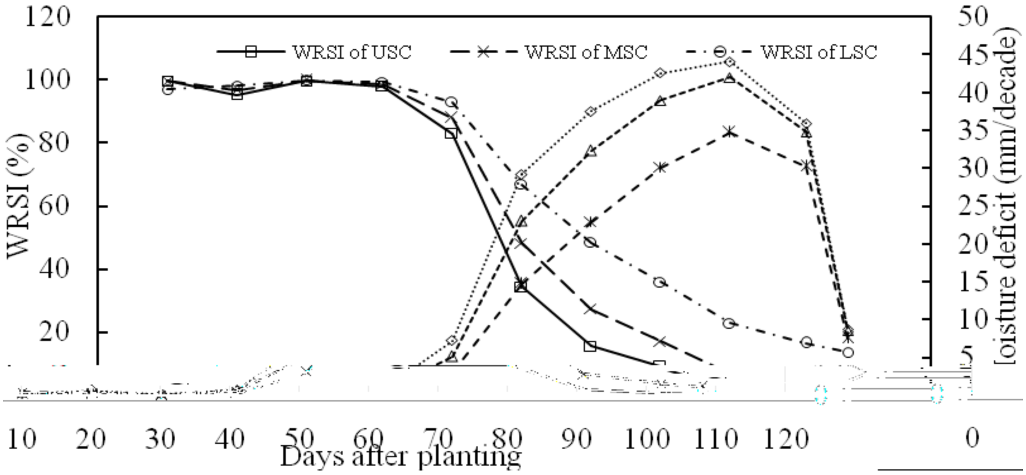

Figure 7: Seasonal variations of water requirement satisfaction index (WRSI) and moisture deficit (MD) of teff farmlands in Bella-Weleh catchment. USC = Upper sub-catchment, MSC =Middle sub-catchment, LSC =Lower sub-catchment

The water requirement satisfaction indices under *teff* farmlands of the catchment followed the trend of moisture deficit but in opposite direction. Between sowing and 40 days after sowing, there was high WRSI in all the farmlands, as this period (between late July and mid August) received relatively high rainfall. Between 40 to 90 days after sowing, the WRSI steadily decreased and reached the lowest value at the end of the crop period. Between 90 to 105 days after sowing, the WRSI of the upper sub-catchment farmlands reached zero before the crop has finished its lifecycle, indicating the presence of critical moisture deficit in the sub-catchment. The farmlands of the lower sub-catchment had relatively better WRSI during the dry periods compared to the farmlands of the other two sub-catchments.

Classification of farmlands based on the barley, wheat and teff WRSI

The values indicate that the WRSI of *teff* boe!x i fbu x fsf! jo! u f!sbohf! pg '’dspq! gbjmsf ! boe! ’t bujtgbdupsz !sbujoh !sftqfdujwfmz !x i fsfbt! u bu!pg c bsfmz! x bt ! po! bwfsbhf ! befrvbuf!

throughout the crop cycle. The results further signify that the two crops, wheat and *tef*, will face chronic terminal moisture deficit when grown in the three sub-catchments of Bela-Weleh catchment. The classification of the sub-catchments as per their WRSI of the three crops is illustrated in Figure 4.

The results indicate that, as the rainfall distribution is very poor and concentrated in two months, the choice of planting time and the length of the crop cycle are very important scenarios to be considered. Barely had better WRSI because of relatively early planting and shorter cycle of the crop. On the other hand, wheat experienced some terminal moisture stress owing to its relatively late planting and longer crop cycle. Similarly, *teff* had the lowest WRSI due to very late planting and relatively longer crop cycle than barely and wheat.

It would be advisable to look the yield data and yield potentials of the crops. *Teff* and wheat can give above 2 tons/ha (personal contact with Wereda Bureau of Agriculture and Rural Development experts) while in the catchment, they gave even less than 0.5 ton/ha. As a comparison, barley can give reasonable yield with appropriate agronomic practices other than moisture conservation packages as the soil nutrients are depleted. The differences in yield of barley would have been because of the dry spell that has occurred during the growing season and soil nutrient status across the catchment. Next to barley, wheat can give relatively acceptable yield as the WRSI values are satisfactory, but can be enhanced by practicing soil and water conservation technologies and application of supplemental irrigation. For *teff*, especially in the upper and middle sub-catchments, there is a need to apply supplemental irrigation.

The overall maximum crop evapo-transpiration of barley were 227.9 mm, 231.6 mm and 227.9 mm in the upper, middle and lower sub-catchments, respectively. The determined actual evapo-transpiration of barley were 195.1 mm, 203.3 mm and 208.2 mm in the upper, middle and lower sub-catchments, respectively. There was minimum yield differences of barley among the farmlands observed as the range was 0.05 ton/ha.

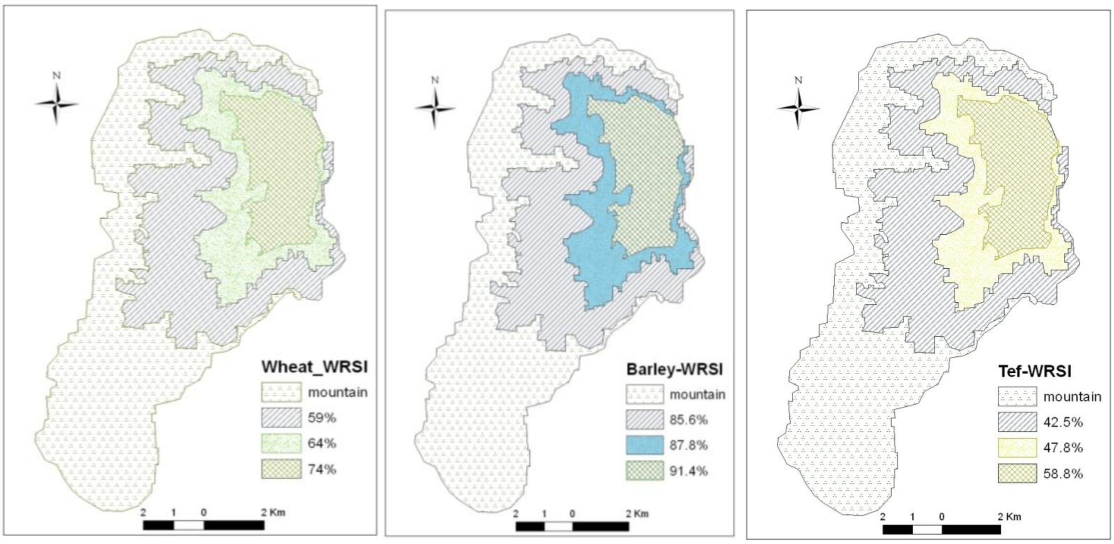

Figure 8: Map of seasonal water requirement satisfaction indices of wheat, barley and *teff*

The actually transpired amount of water by wheat were 179.7 mm, 197.5 mm and 226.8 mm in the upper, middle and lower sub-catchments, respectively. From these differences in the potential and actual evapo-transpiration could result in yield differences in the catchment. There was a moderate yield difference of wheat among the farmlands observed as the range was 0.19 tons/ha.

The seasonal maximum evapo-transpiration of *teff* were 336.2 mm, 342.0 mm and 344.9 mm in the upper, middle and lower sub-catchments, respectively. There was high difference in the actual evapo-transpiration of *teff* across the farmlands and it was 139.5 mm, 159.3 mm, and 201.0 mm in the upper, middle and lower sub-catchments, respectively. When compared with the above two crops, *teff* actually evapo-transpired less than the potential evapo-transpiration. The yield difference of *teff* between the upper and lower sub-catchments was high and maximum as the range was 0.43 tons/ha which doubles the yield obtained in the upper sub-catchment farmlands.

Soil Moisture Depletion with Soil Depth across the Farmlands

The lowest mean difference, which was 4.05 mm and non-significant in mean difference, was observed in the upper sub-catchment farmlands of barley in the 40-58 cm soil depth because of its shallow depth and the associated little capacity to store adequate moisture (Table 3a). Similarly Gregory (1989) and Sharma (1990) reported that shallow root depth has no significant role in moisture retaining for extended dry spell periods for crops. The mean difference among the soil moisture depletion in the farmlands and respective soil layers are significant except in the 40-58 cm and 40-70 cm soil depths of the upper and middle sub-catchment farmlands, respectively. On the other hand, the maximum mean difference at wheat farmlands was 43.18 mm in the lower sub-catchment in the 40-85 cm soil layer, preceded by the upper 0-40 cm depth with a mean difference of 31.51 mm (Table 3b). This result is in line with the work of Penna et al. (2009), who from inspection of soil moisture data time series, reported that hill slope-averaged data over different depths are relatively close to each other after rainfall events, and their difference increases with time during the dry-down. The soil moisture depletion in the *teff* farmlands increased to a maximum from 40 days after sowing to harvesting time and this period indicates the extent to which *tef* crop suffered from the moisture deficit due to exhaustion of the available soil moisture (Table 3c). The 0-40 cm soil layer in the lower sub-catchment farmlands was high and above from all the layers in the soil moisture depletion trend signifying the ability to store and release moisture.

Conclusion and Recommendation

The climate and environmental resource base of crops play a dominant role in their survival, growth, development and ultimate yield production from which almost all food chains start. In the Ethiopian condition, rainfed agriculture plays and will continue to play a dominant role in providing food and livelihoods for an increasing population. The rainfall is very erratic, unpredictable and drought occurs very frequently. Due to continuous cultivation with low input to return the mined nutrients and organic matter content washed by erosion on the northern part of Wollo, soils of this region are shallow in depth, have very low moisture retention capacity and low organic matter. These adversities of climate and soil resulted in the prevalence of soil moisture deficit for most of the year, which led to the loss of crop production.

Considering the average seasonal water requirement satisfaction index of the crops, the WRSI in all the sub-catchments was adequate for barely, satisfactory for wheat and very low resulting in crop failure for *teff*. Soil moisture depletion trends in all the sub-catchments also followed the rainfall trend and were high during dry periods and low during wet periods although there were considerable differences in the level of depletion among the sub-catchments. In this catchment and similar agro-climatic areas, barley can give reasonable yield with rainfed cropping system without practicing water conservation practices and/or supplemental irrigation concerning water shortage and its influence. On the other hand, supplemental irrigation and/or water conservation structures should be practiced during the rainfed cropping system in order to get the potential yield of *teff* and wheat in this catchment and similar agro-climatic areas, especially in the sandy-to-sandy clay loam texture farmlands.

Table 3: One-way sample t-test of soil moisture depletion (mm) with depth under barley (a), wheat (b) and teff (c) farmlands

(a)

	t	Df	Sig. (2-tailed)	Mean Difference	Std. Error Mean	Std. Error Mean	95% Confidence Interval of the Difference	
							Lower	Upper
SD of USC 0-40 cm	2.59*	7	0.036	14.16	15.45	5.46	1.24	27.08
SD of USC 40-58 cm	1.73	7	0.127	4.05	6.61	2.34	-1.48	9.57
SD of MSC 0-40 cm	3.25*	8	0.012	21.09	19.48	6.49	6.11	36.06
SD of MSC 40-70 cm	2.03	8	0.076	10.40	15.35	5.12	-1.39	22.20
SD of LSC 0-40 cm	4.64**	7	0.002	45.28	27.59	9.76	22.21	68.35
SD of LSC 40-85 cm	4.18**	7	0.004	67.53	45.72	16.16	29.31	105.75

(b)

	t	Df	Sig. (2-tailed)

(c)

	t	Df	Sig. (2-tailed)	Mean Difference	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference	
							Lower	Upper
SD of USC 0-40 cm	4.46**	10	0.001	19.76	14.68	4.43	10.51	28.86
SD of USC 40-58 cm	3.74*	10	0.004	7.09	6.29	1.90	3.90	12.91
SD of MSC 0-40 cm	4.42**	10	0.001	24.08	18.06	5.45	14.72	37.58
SD of MSC 40-70 cm	3.61*	10	0.005	12.59	11.56	3.48	7.53	25.97
SD of LSC 0-40 cm	5.58**	10	0.001	35.59	21.15	6.38	24.96	56.07
SD of LSC 40-85 cm	5.36**	10	0.001	32.19	19.91	6.00	22.73	69.45

t-values with *,** are significant at 0.05 and 0.01 significant level
USC = Upper sub-catchment, MSC =Middle sub-catchment, LSC =Lower sub-catchment

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PART 5

REFERENCE EVAPOTRANSPIRATION, HYDROLOGY AND IMPACT OF CLIMATE CHANGE ON WATER RESOURCES