OPTIMIZING CROPPING PATTERN AND WATER PRODUCTIVITY: THE CASE OF UPPER AWASH AGRO INDUSTRY ENTERPRISE IRRIGATION SCHEME

By

Dinsefa Shafi Abdrshkur

A Thesis Submitted to the Department of **Water Resources Engineering**

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in **Water Resources Engineering** Specialization in **Irrigation Engineering**

Office of Graduate Studies

Adama Science and Technology University

Adama, Ethiopia

February, 2019

OPTIMIZING CROPPING PATTERN AND WATER PRODUCTIVITY: THE CASE OF UPPER AWASH AGRO INDUSTRY ENTERPRISE IRRIGATION SCHEME

By

Dinsefa Shafi Abdrshkur

Advisor: Dr. Zelalem Biru

A Thesis Submitted to the Department of **Water Resources Engineering**

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in **Water Resources Engineering** Specialization in **Irrigation Engineering**

Office of Graduate Studies

Adama Science and Technology University

Adama, Ethiopia

February, 2019

APPROVAL OF BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the final open defense by **Dinsefa Shafi Abdrshkur** have read and evaluated his thesis entitled "**Optimizing Cropping Pattern and Water Productivity: the case of Upper Awash Agro-Industry Enterprise irrigation scheme** " and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science in **Water Resources Engineering** specialization in **Irrigation Engineering.**

____________________________	____________________	________________
Advisor	Signature	Date
____________________________	____________________	________________
Chair person	Signature	Date
____________________________	____________________	________________
Internal Examiner	Signature	Date
____________________________	____________________	________________
External Examiner	Signature	Date

DECLARATION

I hereby declare that this MSc.Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Dinsefa Shafi Abdrshkur

Signature:____

This MSc.Thesis has been submitted for examination with my approval as thesis advisor.

Name: Zelalem Biru (PhD)

Signature:____

Date of submission:___________________________

ACKNOWLEDGEMENT

Above all, I would like to thank Almighty Allah for making this thesis success and giving me everything in my life.

My deep appreciation goes to my advisor Dr. Zelalem Biru for his encouragement, advice, support and his valuable guidance throughout the course of this study.

I would like to express my sincere appreciation to Upper Awash Agro Industry Enterprise irrigation and crop department and it respective staff for facilitating and providing relevant data, important information and support during site investigation time. From those Special thanks goes to Mr. Demelash Werku, Mr. Mezgebu Demeke, Mr. Abreham Ashawero, Mr. Demsew Admasu, Mr. Beyene and Mr. Desalegn Derese.

I would like to acknowledge Ethiopia National Meteorological Service Agency and Awash basin Authority for providing the relevant data and information required free of payment. Also I would acknowledge Melkassa Agricultural Research Center for facilitating soil lab equipment and Ministry of Education for providing financial support for the study.

My deepest thank is to my beloved parents. For their unconditional love, inspiration and always encouraging me, support me, and give me strength to go through my study.

.

TABLE OF CONTENTS

LIST OF TABLES

Table **page**

LIST OF FIGURES

Figure **Page**

ABBREVIATION AND ACRONYMS

AwBA	Awash Basin Authority
BCM	Billion Cubic Meter
cm	centimeter
CWR	Crop Water Requirement
dS	deci Siemens
EC_e	Electric Conductivity of soil
EC_w	Electric Conductivity of water
ER	Effective Rainfall
ETa	Actual Evapotranspiration
ETB	Ethiopian Birr
ETc	Crop Evapotranspiration
ETm	Maximum Evapotranspiration
Ewp	Economic Water Productivity
FAO	Food and Agriculture Organization
FC	Field Capacity
g	Gram
IR	Irrigation Requirement
kg	Kilogram
LP	Linear Programming
NLP	Non Linear Programming
Pwp	Physical Water Productivity
UAAIE	Upper Awash Agro Industry Enterprise
USDASCS	United States Department of Agriculture Soil Conservation Service
WP	Water Productivity
WP	Wilting Point
Ya	Actual Yield
Ym	Maximum Yield

ABSTRACT

Scarcity of water during critical irrigation period has intensified at Upper Awash Agro Industry Enterprise irrigation scheme. In addition, adoption of poor irrigation water management and fixed cropping pattern make the scheme low productive in terms of yield, profit and water. The aim of this study was to maximize the net profit of scheme due efficient utilization of the scarce resource among the competing crops through optimizing cropping pattern and water productivity. Irrigation water demand and water productivity in terms of total (effective rainfall plus irrigation), irrigation and crop evapotranspirated water for current cropping pattern of annual crop were assessed. The considered annual crops were tomato, maize, dry beans and cotton. Their irrigation water demand was determined using CROPWAT8.0 model and compare with supplied water; finally nonlinear programming model (NLP) using crop water production function were developed to determine the optimal cropping pattern that gives maximum profit at different crop water allocation scenario. The models applied under full and five different levels of deficit crop water requirement scenario (10%, 20%, 30%, 40% and 50%). Profit maximization being the objective function of the NLP models, monthly and annual irrigation water availability, total land availability, the maximum possible area for tomato due to processing factory capacity and production costs are constraints; area allocation and irrigation water demand of each crop are decision variables. The program solved by Lingo17.o optimization software. The result shows that from the month of July to September, the supply meets the irrigation demand but from month of October to March and end of April to June, supply cannot meet the demand. Water productivity (WP) is expressed in physical and economic term. Physical and economic productivity of tomato, maize, dry bean and cotton in terms of crop evapotranspirated water were 7.57, 0.77, 0.25, 0.35 kg/m^3 and 29.66, 0.90, 0.0 and 2.80 ETB/m^3 respectively. These crop evaptranspirated water productivity values of all crops were higher than total and irrigated water productivity except cotton. For most of crops, the physical productivity in terms of total, irrigation and crop water were below the world average value. The optimal cropping pattern developed under full , 10, 20, 30, 40 and 50% CWR deficit scenario were reduced their total optimal cropping pattern by 48.4, 51, 45.6, 37.3, 54 and 44.4% compared to the existing cropping pattern. However, their net profit and average water productivity increased by 50.80, 33.66, 16.18, 0.33, -13.61 and -22.37% and 80.1, 70.3, 70.1, 51.8, 166.8 and 151.4% respectively compared to existing pattern. Water productivity level of 40 and 50% CWR deficit scenario was very high but with regard to net profit, they were far from the optimal. The optimal cropping pattern developed under full CWR scenario gave the maximum total profit as well as optimum WP compared to existing and all other scenarios. In conclusion, Total optimal cropping pattern in each scenario uses less than 60 % of current irrigation land due to water constraints. However, to irrigate all the existing irrigation land by scientific irrigation strategy, extra water sources are will be needed.

Key words: optimization, cropping pattern, water productivity, net profit, non linear programming,

CHAPTER 1: INTRODUCTION

1.1. Back ground study

The world's readily available fresh water resources are become increasingly scarce due to higher demands by municipal, industrial, recreational and agricultural sectors. This is mostly because of population increase and higher standards of living in many areas, but also due to changes in land use and global climate change as a result of rapid development (Goodarzi *et al.*, 2014). Irrigation accounts for 70% of total freshwater withdrawals globally, with the industrial and domestic sectors accounting for the remaining 20% and 10%, respectively (WwAP, 2014). With expected increases in population by 2030, food demand is predicted to increase by 50% and 70% by 2050 (Bruinsma, 2009). Without improved efficiencies and productivity, agricultural water consumption is expected to increase by about 20% globally by 2050 (WwAP, 2012). Irrigation accounts for more than 40% of the world's production on less than 20% of the cultivated land (WwAP, 2012). Globally, irrigated crop yields are 2.7 times those of rain fed farming; hence irrigation will continue to play an important role in food production (WwAP, 2012). However, the increasing competition for water usage in different sectors is making this resource more scarce and valuable. Hence, today, the agricultural sector around the world is under more pressure for limiting its water use, not only because of the increasing water demand, but also because of climatic changes and more frequent droughts (Homayounfar *et al.,* 2014)

Ethiopia is one of developing country and increasingly investing in irrigation sector in order to exploit the agricultural production potential of the country (MoWR, 2002). Some of the investments are located in Awash River basin, and it is the most developed basin in Ethiopia due to availability of suitable land and water resources for the development of irrigated agriculture (infrastructure and market accessibility). AwBA (2016) confirmed that the irrigated land in the basin reach to 200,000 ha and it uses 83% of the total available river water. Currently, there is an increasing water demand due to rapid population growth, urbanization and establishment of large investment in the basin. Berhe *et al.* (2013); Adeba *et al.* (2015); Kerim *et al.* (2016) and Kerga *et al*. (2017) conducted research on Awash River basin based on water allocation strategies related to current climate change, irrigation expansion scenario and water quality of the river; they conclude that availability of water in Awash River cannot achieve present and future water demand in the basin.

Consequently, Scarcity and decreasing availability of water limit irrigated production overall (WwAP, 2014). These call for increasing water productivity (increasing production per unit area and per unit water). However this needs more scientific utilization of the water resources and their optimal allocation area to achieve maximum returns (Birhanu *et al*., 2015).

There are several large, medium, and small-scale irrigators in the basin. Wonji and Metehara Sugar Plantations, Upper, Middle and Lower Awash State Farms with fruits, vegetables and cotton plantations have been the well-known large-scale irrigation systems in the basin for over 50 years (AwBA, 2017). Upper Awash Agro Industry Enterprise (UAAIE) irrigation scheme is recently privatized large scale irrigation schemes in upper awash valley. Awash River is the major source of irrigation water for the scheme. Recently, the diverted water source reduced due to reduction of flow in the Awash River. Hence, this diverted water cannot meet the crop water demand of existing cropping pattern. Consequently, the crops face water stress. This phenomenon adversely affects yield, water productivity and benefit of the schemes. Therefore, to overcome this constraint decisions requires on how much water and cropping pattern (area) should be allocated to each crops, based on water availability, maximization of benefits, and high water productivity requirement of the scheme.

Daghighi *et al*. (2017) stated that, if available water resources in the irrigation scheme do not fully meet the irrigation water demand of crops, resources exploited and water allocated across different crops should be optimized, in order to minimize the negative effects of water shortage on the benefit of the scheme. In addition, the success of irrigation system operation and planning depends on the quantification of supply and demand or to minimize the gap between the supply and demand (Singh, 2012). Therefore, optimization of cropping pattern is considered as an important approach for irrigation water management and planning and it play an important role in improving irrigation system through increased income levels and water use efficiency (Valipour, 2015; Nazarifar *et al*., 2017). These optimal cropping patterns strategies are achieved by using mathematical model and software facilities (Rabie *et al*., 2015). Therefore, optimization models are required to select optimal solutions, systematically, under agreed-upon objectives and constraints (Wang, 2014).

1.2. Problem Statement

Today, the agricultural sector around the world is under more pressure for limiting its water use, not only because of the increasing water demand, but also because of climatic changes and more frequent droughts (Homayounfar *et al.,* 2014). Awash River Basin is the most utilized river basin in Ethiopia. Competition for water in the basin has intensified in recent years, and there has been an increasing pressure on the schemes to improve water use efficiency (Dejen, 2015). Obviously, increasing water demands in the basin would reduce the water share of the schemes.

Recently, in UAAIE the diverted water source reduced due to reduction of flow in the Awash River. Hence, this diverted water cannot meet the crop water demand of existing cropping pattern. Furthermore, the way of irrigation water determination and application and cropping pattern plan was not scientific rather it is traditional. This all observable fact adversely affects yield, water productivity and profit of the schemes. Apparently, this requires effective irrigation water and cropping pattern allocation that will minimize the impacts of aforementioned problem. Therefore, to address these issues, it is essential to optimize cropping pattern and water productivity. It is worth mentioning that no significant research work carried out related to optimal use of irrigation water and cropping pattern with the scientific irrigation water management practice in these schemes.

1.3. Objective

1.3.1. General objective

The main objective of this study was to maximize the net profit of the scheme by optimizing cropping pattern and water productivity the case of Upper Awash Agro Industry Enterprise irrigation scheme.

1.3.2. Specific objectives

i. To assess irrigation water demand of annual major crops in the scheme.
ii. To determine current water productivity level under existing cropping pattern and water management practice in the scheme.
iii. To develop optimal cropping pattern and water productivity model for maximizing net profit.

1.4. Delimitation /Scope of the Study

The study was conducted at the Upper Awash Agro-Industry Enterprise irrigation scheme. Purpose of choosing this scheme was due to existence of water scarcity and availability of high quality data compared to other vicinity schemes. The scheme produces both perennial horticulture and annual crops in its two farms, namely Nura Era and Merti Jeju, Both of the farms have their own intake canal from Awash River in a separate way. The area coverage of Nura era is two third of total irrigation area of UAAIE and most of its area grow annual crops. For production year 2017/18 1170 ha area of Nura Era farm covered by annual major crop and Merti Jeju 65 ha single annual crop. Due to variation of water supply canal and unavailability of all crops in Merti Jeju, The entire study focused on an irrigation area of annual major crops that grow in Nura Era farm. This study was not taking into account out of annual major crop irrigation area because the scheme grows perennial horticultures and they need long time to collect information. For estimation of potential yield, water - yield relationship were not developed due to unavailability of recorded water data in the past. In the optimization equation, Constraints due to soil salinity was not included because the current soil salinity level was below potential tolerance level of considered crops and it is no effect on the current objectives. This study was to optimize cropping pattern to maximize net profit of the scheme. To achieve this objective, irrigation water demand for the annual crops was determined using CROPWAT 8.0 model and the result compare with the available water supply. Physical and economic productivity level of supplied water determined in terms of total water, irrigation water and crop evapotranspirated water on the existing cropping pattern and finally nonlinear programming model was formulated using crop water production function to optimize cropping pattern by allocating different crop water requirement. Finally, result of this research would help the irrigation managers to make concrete decisions on how much land and water should be allocated to each crop to get more net income out of the available water during irrigation season.

CHAPTER 2: LITERATURE REVIEW

2.1. Water Resource of study area

There are 12 river basins in Ethiopia. Out of these, two are dry, two are water surplus and eight of them are water deficit basins of different levels. The total runoff from these basins was estimated around 122 BCM per year (Adeba *et al.*, 2015). There is always some problem related to water in dry and deficit basins which impacted the livelihood of the community and the development activities. The Awash river basin is one of the river basins of Ethiopia located between $7^{0}53^{'}$N and 12^{0} latitude and 37^{0} 57'E and $43^{0}25$' longitude. It rises at an altitude of about 3000 m a.m.s.l to the west of Addis Ababa, the capital city of the country. Then it flows to the easterly direction and ends at Abbe Lake, the international border of Ethiopia with Djibouti. The river is about 1250-km long (Adeba *et al.*, 2015; AwBA, 2017)

2.1.1. Quantity of water resource.

Berhe *et al*. (2013) conducted a study to analyze the water balance of the Awash Basin under different levels of irrigation development scenario and also determine the water allocation in the Upper, Middle and Lower Valleys of the basin, using a river basin management decision support system. The study result show that Additional storage at or upstream of Koka Dam will be mandatory in near future to satisfy the water demand of the basin.

Kerim *et al*. (2016) study the existing and future water availability under climate change scenario in upper awash sub-basin using hydrologic model and study water allocation of the existing and planned water resource projects for irrigation, hydropower, industries, livestock etc. The study revealed that the base period the annual volume of water is about 1347.9 million m^3 while in the future period the value significantly decreased to1001 million m^3. And result from WEAP analysis show that the annual water demand for the reference period is about 1716.3 million m^3 while the demand increases to 1953.3 million m^3 in the future scenario this is mainly due to expansion of the existing irrigation projects which intern increase the water demand of the projects.

Adeba *et al*.(2015) assessed annual average surface water availability and demand of awash river basin using SWAT model, the model show that around 4.64 Billion Cubic Meters (BCM) available on the study period. And it compared to the estimated demand of about 4.67 BCM in the basin for 1980–2012, the demand exceeds the availability by 0.03 BCM during the study period.

Recently, AwBA (2016) categorized the water uses in the basin as domestic, livestock, irrigated agriculture and industrial. With these water use categories currently the basin provide annual water requirements of 4.114 BCM for 18.6 million human populations, 34.4 million livestock population, 199,234 ha irrigated land and different commercial and industrial activities in the basin (AwBA, 2016). Irrigation water use accounts 83 % of the total water use of the basin. With the consideration of the future human and livestock population growth, irrigation and industrial expansion based on the Growth and Transformation Plan the water demand of the basin estimated as 6.56 BCM (AwBA, 2016).

2.1.2. Quality of water resource

Most of the industries in Ethiopia discharge their waste water into the environment without any form of prior treatment, for several industries the Awash River is used as source for water consumption and for disposing of their waste (AwBA, 2017). Many published and unpublished literatures are available to quantify the quality of Awash River. Some of the literatures related to our study are presented as follow.

Kerga *et al*. (2017) conducted Spatial and temporal water quality dynamics of Awash River using multivariate statistical techniques. Means of the 9 years' (2005-2013) water quality dataset of 19 parameters from 10 stations in the basin were considered. Their study show that Spatial analysis of the sampling sites of the basin as one moves from upper to lower parts of the basin, electrical conductivity, total hardness and chloride decrease in the dry season. However, total hardness slightly increases and total dissolved solids, chloride, and sulfate decrease in the rainy season.

Kerga *et al*. (2017) conducted a research aimed at evaluating Awash River quality status with respect to drinking and irrigation water utilization using water quality index. 17 sample sites were chosen Based on accessibility and land use severity along the river and sampling was done twice in each of the dry and wet seasons. The study shows that the drinking and irrigation water quality indices of the upper basin were found to be poor and marginal categories of the Canadian water quality ranking. Meanwhile, the respective indices for the middle/lower basin, which were lie in the poor and fair ranges of the ranking. Generally, the water quality of the river was below the good rank. In this, they found EC value of Awash River after Lake Koka, Awash River at Koka Dam, Awash River before Lake Koka, and Awash River at Awash Melka Kuntire are 338, 323, 437, and 335.6 μS/cm.

2.2. Crop and irrigation water requirement.

The crop water need (ET crop) is the depth or the amount of water needed to meet the water loss through evapotranspiration. It depends on climate (sunshine, temperature, humidity, and wind speed), crop type and the growth stage of the crop. The influence of the climate on crop water needs is given by the reference crop evapo-transpiration, ETo (FAO, 2012).

Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement represents the difference between the crop water requirement and effective precipitation. The irrigation water requirement also includes additional water for leaching of salts and water to compensate for non-uniformity of water application (FAO, 1998). Irrigation water requirement is the quantity of water that has to be present at crop root region for the crops utilization.

2.3. Yield Response to Water

The yield response to water or the crop water production function expresses the relationship between crop production and evapotranspiration. Empirical models have been developed to analyze the crop water production functions. One of the well-known models is that, applied in the FAO Irrigation and Drainage Paper No-33 (Doorenbos and Kassam, 1979). This model is a simple linear crop production function that enables one to quantify the response of yield to water through a yield response factor (Ky), which relates the relative yield reduction to the relative evapotranspiration deficit. It is assumed that the relationship between the relative yield (Ya/Ym) and the relative evapotranspiration (ETa/ETm) is linear and valid for water deficits up to about 50 percent (i.e. 1-ET a/ETm = 0.5) (Doorenbos and Kassam, 1979).

The water deficit may occur continuously over the total growing period of the crop or it may occur during any one of the individual growth periods (Zhuo and Hoekstra, 2017). In general, for the total growing period, the decrease in yield is proportionally less with the increase in water deficit for crops with Ky<1 while it is proportionally greater for crops with Ky>1. For individual growth periods, the decrease in yield due to water deficit during that growth period is relatively small for the vegetative and ripening periods and relatively large for the flowering and yield formation period (Doorenbos and Kassam, 1979) cited from (Yonas, 2012). Application of the yield response factor for planning, design, and operation of irrigation projects allows quantification of water supply and water use in terms of crop yield and total production for the project area (Yonas, 2012).

2.4. Water productivity

In its broadest sense, water productivity (WP) is the net return for a unit of water used. Improvement of water productivity aims at producing more food, income, better livelihoods and ecosystem services with less water (molden *et al*., 2010).The term refers to the ratio of physical production (in terms of biomass or crop yield) or, in some instances, 'economic value' of production (in terms of gross or net value of product) relative to water use (in terms of water withdrawn, applied or consumed). It is, therefore, expressed in kilograms per cubic meter (kg/m^3) or US dollars per cubic meter (ETB/m^3). The selection of the numerator and denominator depends on the scale and focus of the analysis (Molden, 1997; Molden *et al*., 1998b; Molden and Sakthivadivel, 1999; Jensen, 2007) sited from (Giordano *et al.,* 2017). Further, Water productivity is the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits (molden *et al*., 2010).Water productivity can be expressed either in physical or economic terms (Kumar *et al*., 2009 and Yokwe, 2009) cited from (Teklay and Ayana, 2015). Physical water productivity is defined as the ratio of agricultural output to the amount of water consumed ''more crop per drop'' (kg of product / m^3) and Economic water productivity is defined as the monetary value (it may be net or gross) generated from each unit of water consumed (money/ m^3).

Globally Crop water productivity is well below optimal levels; in many cases farmers have substantial opportunities to improve water productivity (Brauman *et al*., 2013). hence, globally measured average CWP values per unit water depletion are 0.65, 0.23 and 1.80 kg/m^3 for cotton seed, cotton lint and maize respectively (Zwart and Bastiaanssen, 2004)

Zwart and Bastiaanssen, (2004) review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. They found that the ranges of CWP of cotton and maize are (cotton seed, 0.41–0.95 kg /m^3; cotton lint, 0.14–0.33 kg/ m^3 and maize, 1.1–2.7 kg /m^3).

Teklay& Ayana (2015) estimated water productivity of major crops (cotton, sugarcane and onion) grown in upper and middle Awash basin based on surveyed data of 29 irrigation water users from 2005/06 – 2009/10 production year using CROPWAT model. Their study revealed that average physical and economic crop water productivity of cotton was 0.357kg/m^3 and 2.545ETB/m^3 and average physical and economic irrigation water productivity of cotton 0.204 kg/m^3 and 1.7 ETB/m^3.

Finally, high Water productivity of different farm enterprises means getting more profit per drop of water. Producing more crops, livestock, and fish and forest products per unit of agricultural water use holds a key to both food and environmental security. But, for society as a whole, concerned with a basin or country's water resource, this means getting more value per unit of water resource used.

2.4.1. Deficit irrigation

Deficit irrigation(DI) generally refers to fully irrigated crops from which water is withheld during certain tolerant growth stages, and it is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop (Geerts and Raes, 2009). Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water.

DI maximizes water productivity, In other words, DI aims at obtaining maximum WP rather than maximum yields (Zhang and Oweis, 1999). In areas where water is the most limiting factor, maximizing WP may be economically more profitable for the farmer than maximizing yields (English, 1990). For instance, water saved by DI can be used to irrigate more land (on the same farm or in the water user's community), which given the high opportunity cost of water may largely compensate for the economic loss due to yield reduction (Kipkorir *et al*., 2001; Ali *et al*., 2007) cited from (Geerts and Raes, 2009) . Even water transfers from water-rich to water-poor areas are possible.

Deficit irrigation strategies can be divided into two categories (Zhuo and Hoekstra, 2017). (1) Regulated deficit irrigation with non-uniform water deficit levels during the different phonological stages. In this category DI requires precise knowledge of crop response to drought stress, as drought tolerance varies considerably by genotype and phonological stage, and (2) sustained deficit irrigation with uniform water deficit over the cropping period.

2.5. Mathematical programming for optimization

Optimization is a method through which the best possible solution for a problem is determined based on the specified target and the existing constraints (Daghighi *et al*., 2017). All of these values are determined by mathematical functions and relations. The optimized problem has one target function and related constraint conditions encompassing the properties of the system of interest. The common methods of mathematical programming for optimization include linear, non-linear, dynamic and integer programming (Daghighi *et al*., 2017). Recently, the management and planning of water resources have become an important topic in most countries. For this purpose, linear and non-linear optimization methods have been used widely (Akbari, 2016). The linear programming model is a technique for optimization with a linear function subjected to linear equality and inequality constraints that are not always satisfied. However, the non-linear programming model does have linear and nonlinear constraints (Hillier & Lieberman, 1980). Benli & Kodal (2003) used linear and non-linear optimization methods for distributing irrigation water for farms under the limits of water resources in the southeast of Antalya in Turkey. Comparing the results of linear and nonlinear models shows that the non-linear model has more profit than the linear model under the condition of limited irrigation water resources. Kipkorir *et al*. (2002), Ghahraman & Sepaskhah (2004), and Li *et al*. (2015) cited from (mahsafar *et al*., 2017) have conducted studies with the aim of increasing the net income of agricultural products by applying linear and non-linear optimization models to the optimal allocation of water resources to the agricultural sector in terms of the limits of water resources. The results showed that non-linear models offer more benefits than linear ones.

2.6. Optimization of cropping pattern

Cropping pattern is one of the most important parameters involved in crop yield (Montazar *et al.,* 2007). It is directly related to productivity of irrigation systems and greatly contributes to improved land and water utilization. The water resources available in the region of interest do not fully meet the agronomic water need for crops in agricultural lands. Consequently, the plants face water stress and in turn, this results in yield reduction. As a result, the way resources are exploited and water is allocated across different crops should be optimized in order to minimize the detrimental effects of water shortage (Daghighi *et al*., 2017). Niamh *et al.* (2003) conducted a research on optimal cropping pattern to maximize water productivity. The main purpose of the study was to improve water productivity.

Ahmed *et al*. (2012) formulated mathematical sector model to optimize the cropping pattern in Saudi Arabia aiming at maximizing the net annual return of the agricultural sector in Saudi Arabia and ensuring the efficient allocation of the scarce water resources and arable land among the competing crops. The results showed the potential for Saudi Arabia to optimize its cropping pattern and to generate an estimated net return equivalent to about 2.42 billion US$ per year. The optimized cropping pattern in Saudi Arabia has been coupled with about 53% saving in the water use and about 48% reduction in the arable land use compared to the base-year cropping pattern. Tafteh *et al*. (2014) offered a schedule for distributing irrigation water and also an optimal cropping pattern to maximize net benefit and WP. Results revealed that a 30–35% water deficit would result in an increase in WP by 54%

Mahsafar *et al*. (2017) developed a non-linear optimization model with the objective of determination of the water productivity index (WP) using the methods of optimization of cropping patterns and optimal water allocation in the Qazvin plain irrigation network. The proposed model was applied to six different water supply scenarios including 100% and 90%, 80%, 70%, 60%, and 50% of full irrigation volume. The results showed that the scenario of 60% of full irrigation could increase the WP index by 8.5%, while with the implementation of this scenario; the net benefit from the sale of agricultural products was reduced by 28% from the existing conditions in the region. Pingli *et al*. (2016) argued that the water constraint on agricultural production receives growing concern with the increasingly sharp contradiction between demand and supply of water resources. How to mitigate and adapt to potential water constraint is one of the key issues for ensuring food security and achieving sustainable agriculture is Adjust and optimize the cropping systems.

Nazarifar *et al*. (2018) carried out a research on developing of nonlinear programming model for determination of an optimal cropping pattern in deficit irrigation conditions. A non-linear model with the objective function of economical water productivity index (Net profit to water consumption ratio) was combined with a crop growth model and it was evaluated using the data of Shahid Chamran irrigation network. The result show that applying 10 percent deficit scenario , the overall economical water productivity of the network can be increased up to 19% by managing cropping pattern as compared to the full irrigation scenario. While in the 20 and 30 percent deficit irrigation scenarios, the economical water productivity index values increased 21 and 23 percent respectively by implementing optimal cropping pattern.

Birhanu *et al.* (2015) a chance constraint linear programming (CCLP) model was used for optimizing cropping pattern for major crops grown at Koga Irrigation scheme, Ethiopia. The model objectives were yield and benefit maximizations subject to land and water availability constraints. Each objective function has four scenarios. The cropping patterns under yield and benefit maximization models were found to be identical under all scenarios. However, the cropping patterns of each model varied among scenarios. The study showed that the possibility of irrigating 5904.3 to 8051.0 hectares of land at 80% by optimizing cropping patterns at irrigation efficiency of 48%. This could increase the yield by 108 to 153%, benefit by 153 to 208% and physical water productivity by 132% to 186% and economic water productivity by 205% to 241% of the actual values.

2.7. Description of CROPWAT Model

CropWat is a decision support system developed by the Land and Water Development Division of Food and Agriculture Organization (FAO) for planning and management of irrigation (FAO, 1992). CropWat is a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirements, and crop irrigation requirements, and more specifically the design and management of irrigation schemes. For this study, CropWat 8.0 was used. CropWat 8.0 is a computer program for the calculation of crop water requirements and irrigation requirements from climatic, soil and crop data. Furthermore, the program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying crop patterns. So many scholars are used this software for analysis of crop water requirement, irrigation requirement, effective rainfall and irrigation schedule in the country and around the world. Some of scholar used this software in the country's are Mahtsente and Birhanu (2015) used for water demand and irrigation requirement analysis for major crops in holleta catchment. Darshana *et al*. (2012) used for estimation of crop water requirement analys in holeta chatchment. Yewendwosen and Zinabu (2015) used for evaluating the water management of irrigated sugarcane production in wondogenet, south Ethiopia. Sisay (2016) used for evaluating irrigation water management in the upper blue nile basin,Ethiopia(Koga irrigation scheme). Teklay and Ayana (2015) used for the analysis of cropevaptranspiration, effective rainfall and irrigation requirement in awash river basin

2.8. Description of LINGO Optimization Tool (software)

LINGO is a comprehensive tool designed to make building and solving mathematical optimization models easier and more efficient. LINGO provides a completely integrated package that includes a powerful language for expressing optimization models, a full-featured environment for building and editing problems, and a set of fast built-in solvers capable of efficiently solving most classes of optimization models. LINGO's primary features include Algebraic Modeling Language, Convenient Data Options, Model Interactively or Create Turnkey Applications, Extensive Documentation and Help, and Powerful Solvers and Tools.

LINGO is available with a comprehensive set of fast, built-in solvers for linear, nonlinear (convex & non-convex), quadratic, quadratically constrained, and integer optimization. You never have to specify or load a separate solver, because LINGO reads your formulation and automatically selects the appropriate one. Solvers and tools available in LINGO are as follows: General Nonlinear Solver, Global Solver, Multistart Solver., Barrier Solver, Simplex Solvers, Mixed Integer Solver, Stochastic Solver, Quadratic Recognition Tools, Linearization Tools and Model and Solution Analysis Tools.

LINGO includes a comprehensive set of analysis tools for debugging infeasible linear, integer and nonlinear programs, using advanced techniques to isolate the source of infeasibilities to the smallest subset of the original constraints. It also has tools to perform sensitivity analysis to determine the sensitivity of the optimal basis to changes in certain data components (e.g. objective vector and right-hand-size values) (LINDO systems Inc., 2017). Currently so many scholars are used this software for optimization purpose. From those Mahsafa *et al*. (2017) used to optimize allocation of agricultural water for irrigation of multicrops using nonlinear programming. Shreedhar *et al*. (2015) used lingo software for optimizing cropping pattern as a linear programming for markandey command area. Again Mahsafar *et al*. (2017) used for effective agricultural water management. Hassan and Ahmed (2015) used to optimize water supply and cropping area for irrigation. Sahoo and Dash(2016) used as a tool for optimizing fuzzy chance constraints of single period inventory model and finaly Birhanu *et al*. (2015) used for optimizing cropping pattern using chance constraints of linear programming for koga

CHAPTER 3: MATERIALS AND METHODS

The present study deals with optimizing cropping pattern and water productivity. Therefore, in this chapter detail of data collection, data preparation and data analysis and method used are presented.

3.1. Description of study area

This research study was conducted at Upper Awash Agro-Industry Enterprise irrigation scheme. It is located in Awash River basin at oromiya region in arsi and east-shoa zone; as shown in (figure.3.1). It is far from Addis Ababa by 174 km along Awash River in the upper Awash River basin, Ethiopia. The study area lies at an altitude of 1100 - 1200 meters above sea level and located at a latitude range of 8°23’ to 8°45’ N and longitude range of 39°33’ to 39°50’ E. The average annual rainfall is 500 mm with annual minimum and maximum temperature of 13 ^{o}c and 31 ^{o}c respectively. The total area of land under the ownership of the enterprise is more than 4900 hectares. From these, 1957 hectares covered by perennial crops, 2537 hectare is allowed to annual crops such as tomato, dry beans, and cotton and maize and the other remaining hectares are held by bushes and infrastructures.

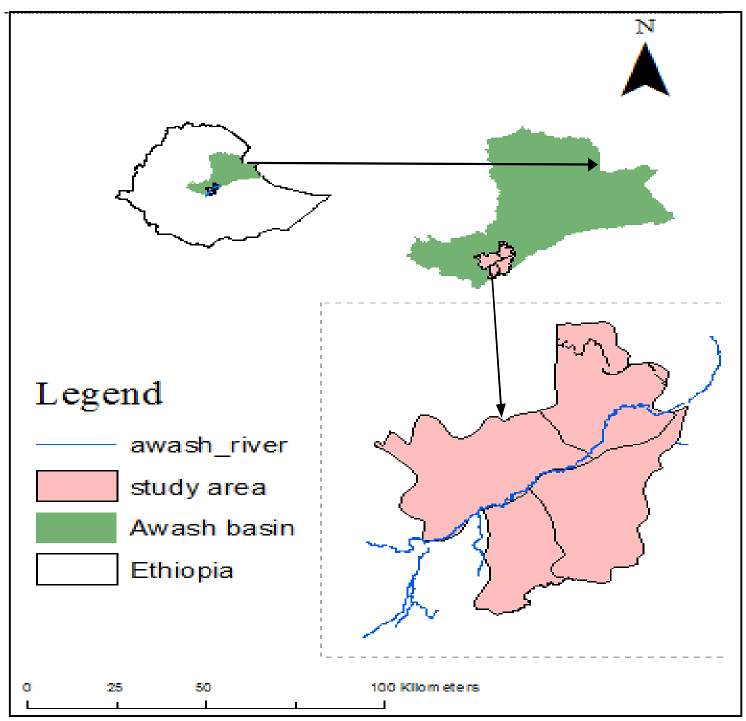

Figure 3.1 location of study area

3.2. Data collection

Primary and secondary data are important for the execution of the study was collected from study site and different respective organization. Accordingly, all the required data are presented in the following sub- heading.

3.2.1. Primary data collection

Soil in the study area was studied to characterize its physical properties and that is important input for CROPWAT 8.0 model for determination of irrigation water. For this purpose Soil samples were collected from study site at two random representative places, with representative crop root depths of 0-30, 30-60 and 60-90 cm. The two place samples were composed (merged) in each depth and the composite samples were analyzed for, field capacity (FC), wilting point (WP), Soil pH, and electrical conductivity (EC) using standard procedures. Laboratory Determination of bulk density (dry weight), pH, and EC were carried out at Melkasa Agricultural Research Center, soil laboratory. Soil moisture at (FC) and (WP) were carried out at Oromia Water Work Design and Supervision Enterprise at soil and water quality laboratory (Addis Ababa). Infiltration rate was also important parameter for determination of irrigation water demand and it is measured by using double infiltrometer at the study site.

The bulk density was determined using undisturbed soil samples which were collected from three representative crop root depths (0-30 cm, 30-60 cm and 60 - 90 cm), by core sampler with known cylindrical volume. Then the sample was oven dried for 24 h at 105°C and weighed for determination of dry weight. The bulk density was then calculated as:

$$\rho b = \frac{Wd}{VT} \quad . \qquad 3.1$$

Where, ρ_b is bulk density (g/cm^3), Wd is weight of dry soil (gram) and VT is total sample volume (cm^3).

CropWat Model requires the Total soil Available Water (TAW), which represents the total amount of water available to the crop. It is the difference in soil moisture content between

Field Capacity (FC) and Wilting Point (WP). After laboratory determination of soil moisture at FC and WP, TAW was determined using the equation 3.2

$$TAW=1000(FC\ \% - WP\ \%)\,\frac{\rho b}{\rho w}\,Zr \qquad 3.2$$

Where, TAW is the total available soil water content (mm), Zr is crop root depth (m), FC% and WP% percent of moisture content at field capacity and Wilting point ρb is bulk density of soil sample and ρw is density of water.

3.2.2. Secondary data collection

3.2.2.1 Various crop coefficient data

Secondary data like crop coefficient approach for each growing stage (kc), length of crop development stages , maximum root depth and depletion fraction for estimation of crop water requirement were collected from (FAO,1998). While the yield response factors (Ky), used in CROPWAT 8.0 model to estimate crop water requirement and to evaluate water productivity at different water stress level, were taken from (FAO, 2012). Prediction of the reduction in crop yield due to salinity and Crop salt tolerance limit was taken from (FAO, 1985a). All these value attached in appendix Table 1 to 4.

3.2.2.2 Crop data

Upper Awash Agro Industry Enterprise irrigation scheme build up multi crops irrigation system. The enterprise mainly produces horticulture, annual crops and vegetables. Horticulture uses basin irrigation system and the actual amounts of water not know it is assumption but the current study needs actual water data. For this purpose it needs continuous measuring of amount of delivered water to the horticulture from beginning to the end of the production year and it takes long time. Due to time limit it is not consider in the study. For this particular study annual major crops were considered. Those are cotton, maize, tomato and dry beans. Area coverage, planting date, actual yield, potential yield and cost of production for each annual major crop for irrigation season 2017/18 were collected from UAAIE crop department. Costs of production include machinery, manual, fertilizer, chemical and seedlings were present in appendix Table 9.

The potential yields of annual major crop obtained in the scheme with the optimum irrigation management (disease free, under optimum soil water and fertility conditions) were attached in appendix Table 7. Also, Average selling price of each annual major crop grown in the scheme for production year 2017/18 were collected from finance and marketing office of the enterprise. And, their values attached with potential yield at appendix Table 7.

In this scheme, tomato and dry beans were produced two times in a year. Those times are 1) pre production season, time period from September to January and 2) post production season, which covered the irrigation season from February to June. The rest of two months considered as rainfall month and in those month irrigation application reduced.

3.2.2.3 Climate Data

Climate data such as maximum and minimum temperature, wind speed, sunshine hour, humidity and rainfall are important input for irrigation water demand. For 30 years (1988 to 2017) data recorded by nearest station (Abomsa Metrological Station) to the irrigation scheme was collected from office of National Metrological Agency. Their Average monthly value was attached in appendix Table 5.

3.2.2.4 Irrigation Water Utilization

The only Source of irrigation water for Upper Awash Agro Industry Enterprise irrigation scheme is Awash River. UAAIE irrigation scheme irrigate throughout the year and it abstract water from three intake gates. Those gates are Abadisga pump, Nura era main diversion weir and Merti Jeju diversion weir. This study, focus on Nura era main diversion weir flow. To irrigate annual crop the scheme uses 'siphon' water measuring and conveying instrument to convey water from the main canal to the field canal and furrow. Discharge capacity of the siphon is five liter per second (5 l/s). Two siphon uses for irrigating tomato and dry bean with a capacity 10 l/s to irrigate 0.5 ha per day. Maize uses three siphons to irrigate 0.75 ha per day and uses of four siphons for irrigation of 1 ha cotton per day. 1day is 8 working hour. Based on this strategy, amount of water used by each annual major crop were collected from the UAAIE irrigation department and attached in appendix Table 12.

3.2.2.5 Water utilization cost

Awash Basin Authority can collect fees on volumetric basis with an initial objective of covering the running cost of the authority including monthly salary of employees (Teklay and Ayana, 2015). Individual users are charged according to their annual consumption of irrigation water with a charging rate of 3 ETB per 1000 m^3, and all legal irrigation water users in the basin are charged 78.18 ETB per hectare per year for the service provided by the authority in addition to the water fee. Users abstracting water with gravity are additionally charged 5.92 ETB per hectare per year to cover monthly salaries of gate operators (Teklay and Ayana, 2015). This entire fee was incorporated in Nura Era irrigation scheme.

3.3. Data analysis

3.3.1. Assessing annual irrigation water demand of annual major crop

Irrigation water demand is total amount of water that needed by the plant to grow and for other irrigation execution like pre-irrigation and leaching requirement. In order to determine total irrigation water demand for annual crops, analysis of reference evapotranspiration, effective rainfall, crop water requirement, net irrigation requirement and irrigation requirement due to salinity and efficiency are important. They are presented in detail in the following sub-section.

3.3.1.1. Reference Evapotranspiration (ETo)

ETo is the evapotranspiration rate from a reference surface (FAO, 1998). It is a climatic parameter and can be computed from weather data. Also it expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (FAO, 1998). CROPWAT 8.0 model was used for the estimation of reference evapotranspiration, crop water requirements and irrigation requirement. The model uses the penman Monteith method to calculate reference evapotranspiration using a climatic data of 30 year monthly maximum and minimum temperature, sunshine hour, wind speed and humidity. The Penman Monteith approach is a combination of both aerodynamic and radiation terms as reported by (FAO, 1998)

3.3.1.2. Effective rainfall

Effective rainfall refers to the portion of the rainwater that is retained in the root zone of the plants. Not all rainfall is effective because part of rainwater may be lost due to canopy interception, surface runoff, deep percolation or evaporation (Dorenbos and Pruitt, 1992). In this, effective rainfall was calculated based on 30 years monthly rainfall data using USDASCS method in CROPWAT 8.0 model. Empirical equation of USDASCS method is as follows:

$$ER = TR * \left(\frac{125 - 0.2 * TR}{125}\right) \quad \text{(For TR<250mm)} \quad 3.4$$

$$ER = 125 + 0.1 * TR \quad \text{(For TR> 250mm)} \quad 3.5$$

Where: ER is effective rainfall (mm), TR is Total rainfall (mm)

Effective rainfall of the study area was estimated based on 80 percent dependable rainfall rather than average total rainfall because Rainfall for each period is vary From year to year or continuously vary for two and three years this variation affect the designed irrigation project(Doorenbos and Pruitt, 1992). Therefore, 80 percent probable rainfall of each month was used as total rainfall in USDASCS method in CROPWAT 8.0 model.

In order to prepare 80% dependable rainfall, monthly rainfall data for 30 years were ranked in descending order in Excel spreadsheet and the plotting position of each ranked value was determined using the Weibull plotting formula (Doorenbos and Pruitt, 1992) presented below. And their value attached in appendix Table 6.

$$P = \left(\frac{m}{N+1}\right) * 100 \quad 3.6$$

Where, P is the plotting position, m is the rank, number with m = 1, for the highest value and N is the total number of available data.

3.3.1.3. Crop Water Requirement

Crop water requirement is the amount of water required to compensate the evapotranspiration loss from the cropped field. The values for crop evapotranspiration and crop water requirement are identical (FAO, 1998). Values of crop water requirement of each crop obtained by estimation of crop evaporatnspiration. CROPWAT 8.0 model was used for determing crop evapotranspiration using input data of climatic, crop and soil data. The climatic data include monthly maximum and minimum temperature, wind speed, sunshine hours, relativity humidity and rainfall. Crop data consisting of the planting date, crop coefficient data files (including Kc values, ky value) and area of each crop (0-100% of the total area) and also soil data files (total soil moisture content, maximum infiltration rate, depletion fraction and maximum root depth). Then, CWR was computed using the following formula.

$$ETc = ETo * kc \quad , ETc = CWR \qquad 3.7$$

Where, ETc is crop evapotranspiration, ETo is reference evapotranspiration, kc is crop coefficient approach

3.3.1.4. Irrigation Water Requirement

The difference between crop water requirement and effective rainfall give irrigation water requirement. Thus, irrigation water requirement was determined based on the following equation.

$$IWR = CWR - ER \qquad 3.8$$

Where**,** ER is effective rainfall, IWR is Irrigation Water Requirement.

3.3.1.5. Irrigation Demand Including Leaching

To estimate the leaching requirement, irrigation water salinity (ECw) and the crop tolerance to soil salinity (ECe) must be known. Therefore, for this study EC_w of Awash River around study site obtained from (kerga *et al*., 2017) and ECe value for the considered crop obtained from (FAO, 1985) the values are presented in (appendix Table 4). The necessary leaching requirement (LR) estimated for annual major crops, (Rhoades 1974; and Rhoades and Merrill 1976) leaching requirement equation should be used cited (FAO, 1985)

$$LR = \frac{EC_w}{5\left(EC_e\right) - EC_w} \quad 3.9a$$

Where, LR is the minimum leaching requirement needed to control salts within the tolerance (EC_e) of the crop with ordinary surface methods of irrigation, EC_w is salinity of the applied irrigation water in dS/m and EC_e is average soil salinity tolerated by the crop as measured on a soil saturation extract.

The total annual depth of water that needs to be applied to meet both the crop demand and leaching Requirement was estimated by the following equation (FAO, 1985a).

$$AW = \frac{ET}{1 - LR} \quad 3.9b$$

Where, AW is depth of applied water (m^3/year), ET is total annual irrigation water (m^3/year) and LR is leaching requirement expressed as a fraction.

Usually inefficiencies of water application satisfy the leaching requirement and additional leaching is wastage of water. Therefore the computation of leaching water requirement depends on application efficiency of the irrigation scheme and salinity level of the soil.

3.3.1.6. Irrigation demand including Irrigation efficiency

To account for the water losses during conveyance and application to the field, an efficiency factor is used in the calculation of irrigation water demand(Wu and Chen, 2013). The efficiency normally consists of three components, and they represent the water losses through conveyance, distribution and field application. For this study irrigation efficiency obtain from Awash Basin Authority water allocation strategy study plane (AwBA, 2017). It revealed that the irrigation practice in Awash Basin include surface irrigation system with existing efficiency of 35-40%, siphon, (40-45%), sprinkle (55%) and drip (60%) (WWDSE, 2013) cited from (AwBA, 2017). Irrigation efficiency of 45% was considered for the study because the considered crop use siphon. Therefore, irrigation water demands of the crop calculated as net irrigation requirement divided by irrigation efficiency of the scheme.

$$\text{Total irrigation demand} = IR/\eta \quad 3.10$$

Where, IR is irrigation requirement, η is irrigation efficiency

After assessing irrigation water demand for the major crop, comparison was made with available supplied water. This is important for clarifying the available water supply was scarce or not, and it was important evidence for the research problem mentioned in introduction section and it gives clue about the further investigation.

3.3.2. Determination of current water productivity level under existing condition

Water productivity can be expressed either in physical or economic terms (Kumar *et al.*, 2009 and Yokwe, 2009) cited from (Teklay and Ayana, 2015). Physical water productivity is defined as the quantity of the product (yield) divided by the amount of water used (kg/m^3). Economic water productivity is defined as economic value (the cash value of output) either gross benefit or net benefit of the product per unit volume of water used.

In this study, the Physical and economic water productivity of the irrigation scheme was analyzed based on (Dong *et al.*, 2001) water productivity indicators. Those indicators are total water productivity, irrigation water productivity and crop water productivity; their physical and economic productivity equations are presented in Table 3.1. In this study, analysis of economic water productivity uses net profit rather than gross profit.

Table 3.1.physical and economic water productivity indicators

S/No	Water productivity indicator	Physical productivity(kg/m^3)	Economic productivity(ETB/m^3)
1	Total water productivity(WP_T)	$\frac{Ya}{ER + DW}$	$\frac{Ya * a - Tc}{ER + DW}$
2	Irrigation water productivity(WP_I)	$\frac{Ya}{DW}$	$\frac{Ya * a - Tc}{DW}$
3	Crop water productivity(WP_C)	$\frac{Ya}{ETc}$	$\frac{Ya * a - Tc}{ETc}$

Where, Ya is actual harvestable yield in kg, ER is effective rainfall in m^3 (ER in mm multiplied by crop area (ha) in each month), DW is diverted (supply) irrigation water to the command area in m^3, ETc is crop evapotranspiration, and a is monetary value of harvestable yield in (ETB/kg), Tc is total cost that is cost of total production and irrigation water cost (ETB).

Important data for determination of water productivity are available in appendix table. Value of ETc in m^3 estimated as the sum of net irrigation applied and effective rainfall.

$$ETc = DW * \eta + ER \qquad 3.11$$

Where, η is irrigation efficiency

Physical and economic water productivity of annual major crops was analyzed based on the equation (Dong *et al*., 2001) water productivity indicators.

3.3.3. Optimal cropping pattern under different deficit CWR

To achieve sustainable and successful agriculture, the available water and land resources must be used to produce crops that can bring about a combined maximum WP and maximum economic net benefit. Deficit irrigation is important strategies to optimize water productivity. Therefore, Optimization of cropping pattern and water allocation in deficit irrigation condition can play an important role for improving water productivity and maximizing net benefit. However, in deficit irrigation conditions, the amount of crop production per unit area is reduced, but ultimately benefit or crop yield per unit water consumed is increased (Sepaskhah *et al*., 2007). Therefore, in this optimization model six alternative deficit crop water requirement scenarios were proposed.

3.3.3.1. Generation of deficit crop water requirement scenario.

These scenarios are described as follows: scenario one allocating full (0% defict) crop water requirement, scenario 2 allocating 10 % deficit of full crop water requirement, scenario 3 allocating 20% deficit of full crop water requirement, scenario 4 allocating 30% deficit of full crop water requirement, scenario 5 allocating 40 % deficit of full crop water requirement and scenario 6 allocating 50% deficit of full crop water requirement through the whole growing stage of the crops as stated (Dronbos and kassam, 1979).

3.3.3.2. Formulation of the objective function

The aim of this object function is to maximize farm net profit through optimize cropping pattern and water productivity by allocating different amount of crop water requirements scenario to the annual major crops. In this study, non linear objective function is formulated due to existence of nonlinear relationship between net profit and irrigation water. The objective function is specified as net profit maximization equation as a function of crop production equation while the constraints are total land availability, monthly and annual irrigation water availability, investment cost and factory capacity constraints. The decision variables are the land area (cropping pattern) and water demand per hectare for each crop in all scenarios.

The following crop water production function was used to derive actual yield in the formation objective function (Doorenbos and Kassam, 1979).

$$\frac{Ya}{Ym} = 1 - Ky\left(1 - \frac{ETa}{ETm}\right) \quad . \qquad 3.12$$

Where, Ya is the actual yield of the crop with the available water (kg/ha), Ym is the maximum yield (kg/ha) that could be obtained when there is no limitation of water (Allen *et al*., 1998). ETa and ETm are the actual and potential crop evapotranspiration (mm), and Ky is the yield response factor of crop for the full growing season. Potential crop evapotranspiration was estimated using CROPWAT 8.0 software.

Actual evapotranspiration (ETa) is in mm estimated as the sum of net irrigation applied and effective rainfall (Berhanu *et al*., 2015)

$$ETa = \frac{R_c * \eta}{A} + ER \qquad 3.13$$

Where, Rc is the irrigation water to crop ‘c’ (m^3), η is the irrigation efficiency, and ER is effective rainfall (mm). A is irrigated area (ha).

In equation 3.14 and above, Irrigation water, effective rainfall and potential evapo-transpiration used as in volumetric bases per hectare per year rather than in depth (mm)

Combining equations 3.12 and 3.13, actual yield Equation (3.14) was developed

$$Ya_c = \sum_{c=1}^{n}\left[\left(Ymc\left(1 - kyc + \frac{kyc*ER}{ETMc}\right)\right) + Ymc * \eta * \left(\frac{kyc}{ETMc}\right)Rc\right] \qquad 3.14$$

Where, c is stands for crop type and n is number of crops.

Therefore, the total net profit (net income) obtained by deducting the sum of production costs of all crops (including water cost and service cost of the basin) from the resulting sum of gross benefit of all the annual major crops.

Thus, the objective function is

$$\text{Max NI} = \sum_{i=1}^{n} \left(Pc_i * Yaci - C_c \right) * Xi - W_p \sum_{i=1}^{n} R_{ci} * Xi - S_P \sum_{i=1}^{n} X_i \qquad 3.15$$

$$Cc = \sum_{i=1}^{n} Cm_{ci} + Cman_{ci} + Csd_{ci} + Cfr_{ci} + Cch_{ci} \qquad 3.16$$

Where, NI is net income(net profit), Pci is the market price of each crops in Ethiopian Birr (ETB) per kg, Yaci is actual yield (kg/ha), Xi is area of crop ‘c’ in hectare, Wp is irrigation water cost per 1000 m^3, Rc_i is irrigation water for each crop per ha/year, Sp is water service cost per hectare per year, Cc is the total cost of cultivation per unit ha except irrigation water cost (ETB/ha) and it includes : Cm_{ci} is cost of machinery, $Cman_{ci}$ is cost of manual (labor), Csd_{ci} is cost of seed and seedling, Cfr_{ci} is cost of fertilizer and Cch_{ci} is cost of chemical for crop ‘ i’ per hectare.

Finally, substituting actual yield equation 3.14 in to equation 3.15 it gives the final objective function as shown below.

Maximize net profit =

$$\sum_{i=1}^{6} \left(\left(Ym_i \left(1 - Ky_c + \frac{Ky_c * ER}{ETM_i} \right) + Ym_i \left(Ky_c * \frac{R_c * \eta}{ETM_i} \right) \right) * Pci - C_{ci} \right) Xi - Wp \sum_{i=1}^{n} R_{ci} * Xi - Sp \sum_{i=1}^{n} Xi \qquad 3.17$$

3.3.3.3 Formulation of constraints

i. Area constraint.

The total irrigable command areas of the upper awash agro-industry enterprise for annual crops are 2537 ha. From this, area occupied by annual crops at Nura Era is 1170 ha for production year 2017/18.

The summation of the land areas allocated for each crop type in the cropping season would be less than or equals the total available land of the study area. Let X_1, X_2, X_3,X_4, X_5 and

X_6 was area occupied by tomato, maize, haricot bean, cotton, tomato2 produced in post season and dry bean2 produced in post production season respectively

Mathematically: Area constraint

$$\sum_{i=1}^{n=6} Xi \leq Xt \qquad 3.18$$

Where, Xi area of each crop starting from area tomato to area of cotton, n is number of annual crop and X_t is total area.

ii. Water constraint

A water constraint of the models was based on the monthly and total irrigation water availability. The source of irrigation water supply is Awash River diverted by using weir. The water supply from the weir varies seasonally depending on the flow of the Awash River. Consequently, water availability is considered on monthly basis in addition to annual volume of available water. Because the area have not water storage access and it uses water directly from the river. Therefore the water constraint is formulated as; the summation of the net monthly irrigation requirement of all existing crops in a particular month (j) is less than or equal to the monthly available water for the scheme multiplied by irrigation efficiency. Similarly, summation of net irrigation requirement of all crops for the whole growing period is less than or equal to the total available irrigation water multiplied by irrigation efficiency.

For those deficits CWR scenario, CWR of the crops was reduced by 10%, 20%, 30%, 40% and 50%. In other words, their CWR was reduced by a deficit factor of (Dc) 0.9, 0.8, 0.7, 0.6 and 0.5. Therefore the net irrigation water requirement was obtained by deducting the effective rainfall (ER) from the product of deficit factor with CWR.

Mathematically; water constraints are:

$$\sum_{i=1}^{n} (Iij * Xi) \leq awj * \eta \qquad 3.19$$

$$\sum_{j=1}^{n} \sum_{i=1}^{n} (Iit * Xi) \leq awt * \eta \qquad 3.20$$

$$\sum_{i=1}^{n}\left(Dc * CWR_{ij} - ER_j\right) * X_i \leq aw_j * \eta \qquad 3.21$$

$$\sum_{j=1}^{n}\sum_{i=1}^{n}\left(Dc * CWR_{ij} - ER_j\right) * Xij \leq awt * \eta \qquad 3.22$$

Where, I is net irrigation water requirement of crop 'i' in a month of j (m^3/ha), X_i is the area covered by the i crop in month j (ha), awj is the total available water in month j (m^3), awt is the total available water from the diversion in the growing period (m^3), Iit is the total irrigation water requirement of 'i' crop in the total growing period (m^3/ha), n is stands for number of months and crops and η is irrigation efficiency.

In equation 3.20 and 3.22 the summation of monthly irrigation water is equal annual irrigation water demand (R/ha)

iii. Factory capacity constraint:

This constraint is incorporated to insure that the production levels of tomato crop were within the factory absorption capacity or need in the enterprise. For this production season the processing machine satisfied by tomato produced with in cultivation area of 213 ha.

$$X_1+X_5 \leq 213 \text{ ha} \qquad 3.23$$

Where,X_1 and X_5 cropping pattern of tomato grown in season one and two respectively.

iv. Investment cost constraints

In UAAIE for production of each annual major crop specific production cost per hectare was determined based on crop production work permit, fertilizer, chemical and seed/seedling requirements. Hence, for production year 2017/18 the following production costs were considered: for tomato per hectare 89820.45 ETB, for maize per hectare 22625.18 ETB, for dry bean per hectare 23503.23 ETB and for cotton per hectare 25202.14 ETB generally the total cost is 42, 541, 768, ETB.

Mathematically investment cost constraints are:

$$89820.45*X_1 + 22625.18*X_2 + 23503.23*X_3 + 25202.14*X_4 + 89820.45*X_5 + 23503.23*X_6 \leq 42541768 \qquad 3.24$$

Decision variable or non negativity constraints

$X_1, X_2, X_3\ X_4, X_5, X_6, R_1, R_2, R_3, R_4, R_5$ and $R_6 \geq 0$ 3.25

Where, R1, R2, R3, R4, R5 and R6 are irrigation water demand /ha/growing season of tomato1, maize, dry beans1, cotton, tomato 2 and dry beans 2 respectively.

After formation of objective function, constraint and decision variable the necessary computation were solved by the Lingo17.0 optimization software. It is a comprehensive tool designed to make solving mathematical optimization models easier and more efficient way. At the end sensitivity analysis of the model was incorporated. Those are reduced cost and dual prices. The reduced cost for the variable is the amount by which its objective function coefficient must be improved before that variable will be a basic variable in some optimal solution and dual price of constraints is the rate of change of the optimal objective value with respect to a small change of right hand side of the constraints

CHAPTER 4: RESULTS AND DISCUSSIONS

Optimizing cropping pattern and water productivity of Upper Awash Agro Industry Enterprise irrigation scheme were done using nonlinear optimization technique. Therefore, in this section results and discussion part of irrigation water demand assessment for annual major crop, determination of current water productivity under existing cropping pattern and water management condition and development of optimal cropping pattern for maximizing net profit of the scheme are presented in details.

4.1. Soil Physical properties of the study area

Soil physical properties of the study site were analyzed; like (bulk density, field capacity and permanent wilting point, infiltration rate, electrical conductivity and PH), most of these properties are an important input for CPROWAT 8.0 software for the determination water demand analysis. The summarized results of these physical properties are presented in Table 4.1. Soil bulk density of the study site varies between 1.35 and 1.61 (gm/cm^3). The top soil surface has slightly lower bulk density than the sub surface and this may be due to compaction of soil in greater depth or due to variation of soil texture. In general, the weighted average bulk density of the soil was found to be 1.46 (gm/cm^3). The pH of the study area varies from top layer 8.23 to 8.7 bottom layer. This indicates that soil is slightly alkaline. The soil has an electrical conductivity of 0.92 dS/m through the 0-30 cm soil depth and it varies from 0.285 to 0.188 dS/m through 30 to 90 cm soil depth. This indicates that the soil is slightly saline and can not affect optimal production of the considered annual crops (FAO, 1985).

Table 4.1 Soil physical properties of study area

sample Depth(cm)	Bulk Density gm/cm^3	PH	EC (dS/m)	Weight bases		
				FC%	WP%	TAW(mm/m)
0-30	1.35	8.23	0.922	35.14	27.82	99.097
30-60	1.42	8.4	0.285	40.33	30.44	140.55
60-90	1.61	8.7	0.1882	40.4	30.46	160.742

The observed average soil moisture content at FC was varied within a range of 35.14 to 40.4 on weight basis. The bottom 60-90 cm and 30-60 cm layer was having larger FC while 0-30 cm soil layers were having lower FC values. The observed soil moisture content at WP was also showed a variation with depth and it lay in a range of 27.82 – 30.46 %. The total soil available water (TAW) is the amount of water that a crop can extract from its root zone was directly related to variation in FC and WP. As a result, high value of TAW was found in the soil depth of 60 - 90 cm; whereas the lower values were observed at 0-30 cm soil depth. The infiltration rate is within the range of 33.67 mm/hr to 37.02 mm/hr. Therefore, the average value was used as input in CROPWAT.8 software. The soil type of the study area was ranging from clay 15% to loam 48%; and it is sandy clay loam (UAAIE project profile, 2007).

4.2. Irrigation water demand for annual major crops in the schemes.

In this section crop water requirement, irrigation water requirement and finally total irrigation water demand for the annual major crops (tomato, maize, dry beans and cotton) were presented in detail.

4.2.1. Reference Evapotranspiration (ETo)

For determination of crop water requirement, computation of reference evapotranspiration is a prerequisite. Figure 4.1 shows the calculated result of reference evapotranspiration. It starts to rise at January and it reach to a maximum point of 5.25 mm/day at June. During March, April, May and June it was above 4.8 mm/day but for the rest of the months in between 4.8 – 4.0 mm/day except December. This Variation happens due to variation of climatic data in each month. For example, maximum and minimum temperature, wind speeds were very high at the month of June (appendix Table 5) and these causes for the increment of ETo in the month of June.

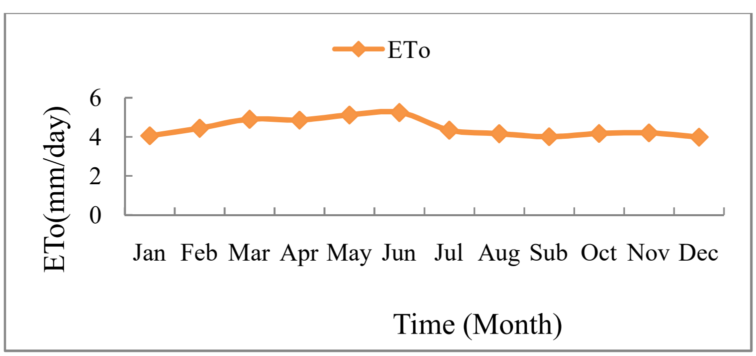

Figure 4.1 Monthly reference evapotranspiration for the study area

4.2.2. Effective Rainfall

The result of effective rainfall, 80% dependable rainfall and 30 years monthly average rainfall for the study area were presented in figure 4.2.

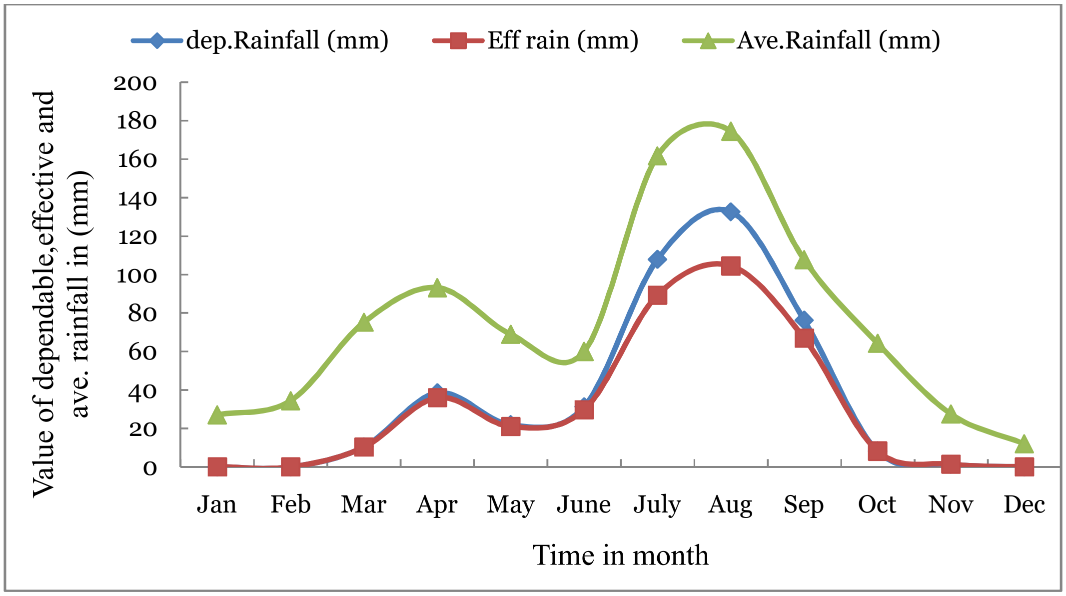

Figure 4.2 Effective, 80% dependable and average rainfall

As shown in figure 4.2 the effective rainfall increasing from February to April and June to august. This shows that the rainfall trend in the study area was bimodal. Comparatively, effective rainfall from month of March to May and June to September was high. On top of this the peak value occurs at the month of august. Also, 30 years monthly average rainfall value have similar pattern as effective rainfall but it lay above effective rainfall though out all month.

4.2.3. Crop water requirement and irrigation water requirement

Crop water requirement of all the major crops were determined by using CROPWAT 8.0 model in terms of crop evapotranspiration. Tomato and dry beans are sowing continuously with an interval of three weeks (in average) throughout the year. These different date sowing crops have different crop water requirement value in the same months. Therefore, for the purpose of determining a united crop water requirement for each crop in each month, average crop water requirement value was adopted for each annual major crop.

These Values of crop water requirement of each annual major crop are presented in table 4.2.

From table 4.2, it can be seen that the total crop water requirement of tomato, maize, dry beans and cotton were 1464.9, 863.7, 1137.4 and 948.9 mm respectively. highest and lowest CWR values of tomato were occur at the month of June (149.5 mm) and September (89 mm), for maize at the month of November (128.5 mm) and July (41 mm).

Table 4.2.Crop water requirement of each annual major crop (mm)

Crops	Tomato	Maize	Dry bean	Cotton
Month				
Jul	147.1	41.0	0.0	115.7
Aug	101.4	58.4	24.8	133.9
Sub	89.0	85.6	69.8	126.7
Oct	104.0	108.6	101.1	117.6
Nov	112.8	128.5	103.3	109.6
Dec	114.2	122.7	94.4	90.1
Jan	128.7	104.8	106.2	-
Feb	114.2	127.1	115.4	-
Mar	145.1	86.9	132.1	-
Apr	122.9	-	131.0	57.1
May	136.0	-	140.7	71.3
Jun	149.5	-	118.5	96.9
Total	**1464.9**	**863.7**	**1137.4**	**918.9**

Crop water requirements of tomato and dry beans were higher than maize and cotton. This is due to continuous sowing and production of those crops throughout the year. Comparatively they have higher CWR at the post production season (January to June). This is due to high values of reference evapotranspiration in this season. Cotton and maize produced once in a year and their total CWR comparatively lower but they sowed with different week or month interval, due to this, the total sowing to harvesting period was increased. On top of this, irrigation water requirement for each annual major crops are determined based on equation 3.8 and the value presented in Table 4.3.

As shown in Table 4.3. Irrigation requirements (IR) of all crops were presented in monthly bases. Total IR of tomato, maize, dry bean and cottons were 1100.6, 677.4, 939.0 and

561.8 mm respectively. The total IR of tomato and dry beans were higher than cotton and maize. These happen due to continuous sowing and production of those crops throughout the year. Therefore, they want more total irrigation water demand than maize and cotton crops.

Table 4.3 Irrigation water requirements of each annual major crop in monthly basis

Crops Month	Tomato IR (mm)	Maize IR(mm)	Dry bean IR(mm)	Cotton IR(mm)
Jul	57.8	0	-	26.4
Aug	0.0	0	0	29.4
Sub	22.0	18.6	2.8	59.7
Oct	95.8	100.4	92.9	109.4
Nov	111.4	127.1	101.9	108.2
Dec	114.2	122.7	94.4	90.1
Jan	128.7	104.8	106.2	-
Feb	114.2	127.1	115.4	-
mar	134.8	76.6	121.8	-
Apr	86.9	-	95.0	21.1
may	115.0	-	119.7	50.3
Jun	119.8	-	88.8	67.2
Total	**1100.6**	**677.4**	**939.0**	**561.8**

Comparatively, maximum IR for all crops occurs from month of November to march; this is due to shortage of rainfall during this period. Furthermore, Cotton has a higher crop water requirement than maize but a lower irrigation water requirement. This is the result of occurrence of more effective rainfall during the peak water requirement period of cotton.

4.2.4. Leaching Requirement

The quality of Awash River (electric conductivity) around at the intake of UAAIE irrigation scheme was show that 0.338 dS/m (kerga *et al*, 2017), and the maximum ECe value of sampled soil was 0.922 dS/m at the shallow root depth. So, this ECe value below 100% tolerance (ECe threshold) level of all annual major crops. Therefore, this ECe value cannot reduce any potential yield. Even if the leaching is required, being the existing irrigation practice in the study area is furrow irrigation, which results in high water lose during irrigation as deep percolation, and it can satisfy the leaching requirement.

4.2.5. Irrigation efficiency

Irrigation water demands of the crop calculated as net irrigation requirement divided by irrigation efficiency of the scheme. This is also the total irrigation water demand of the crops. The value of this total irrigation water demand was presented in table 4.4.

Table 4.4 total water demand for annual major crops grown in UAAIE irrigation scheme

Crops	Tomato	Dry beans	Maize	Cotton
Month	IR demand(m^3/ha)	IR demand(m^3/ha)	IR demand(m^3/ha)	IR demand(m^3/ha)
Jul	1284.7	-	0.0	586.7
Aug	0.0	0.0	0.0	653.6
Sub	488.4	63.0	413.4	1327.4
Oct	2129.8	2065.2	2231.7	2431.8
Nov	2475.0	2263.5	2825.0	2404.0
Dec	2536.9	2097.6	2727.1	2001.7
Jan	2859.1	2360.4	2329.6	-
Feb	2538.2	2565.4	2824.6	-
Mar	2996.5	2707.5	1702.5	-
Apr	1931.4	2111.2	-	468.3
may	2555.9	2659.8	-	1118.1
Jun	2662.2	1973.6	-	1492.9

Note – line indicate that plant are not exist in the field and no water demand and 0.0 indicate that plant in field exist but no need irrigation demand in that month.

4.2.6. Comparison of irrigation water demand and supplied water

Monthly irrigation water demand (m^3/ha) of each annual crop multiplied by respective monthly irrigated area, it gives total water demand value in m^3 and compare with supply water (appendix table 12). The comparisons of total irrigation water demand and supply for annual major crops was presented in figure 4.3. Irrigation water supply was excess from July to September. On the other hand in the month of October, November and December the supplied water cannot meet above 45 % of irrigation water demand. This time was high amount of water demand season, because crop specially cotton and maize totally reach flowering, yield formation and ripening period. From January to March the variation between supply and demand was reduced compared to the former month. But in the month of April supply meet the demand due to reduction of demand and availability of rainfall.

Generally, the irrigation water demand of annual major crops of UAAIE irrigation scheme was higher than available water supply in the month of October to March and end of April to June. This all happen due to under estimation of crop water demand in traditional way and trend of poor irrigation efficiency in the scheme. This finding has important implications for yield reduction. Therefore, to alleviate this problem, supply of adequate water to the crop, with the consideration of losses, are important, use current water saving technology like sprinkler and drip irrigation system to reduce high amount of loses during distribution and application; and also different agricultural water management options should be implemented like area allocation of crop based on water demand due consideration of available water resource.

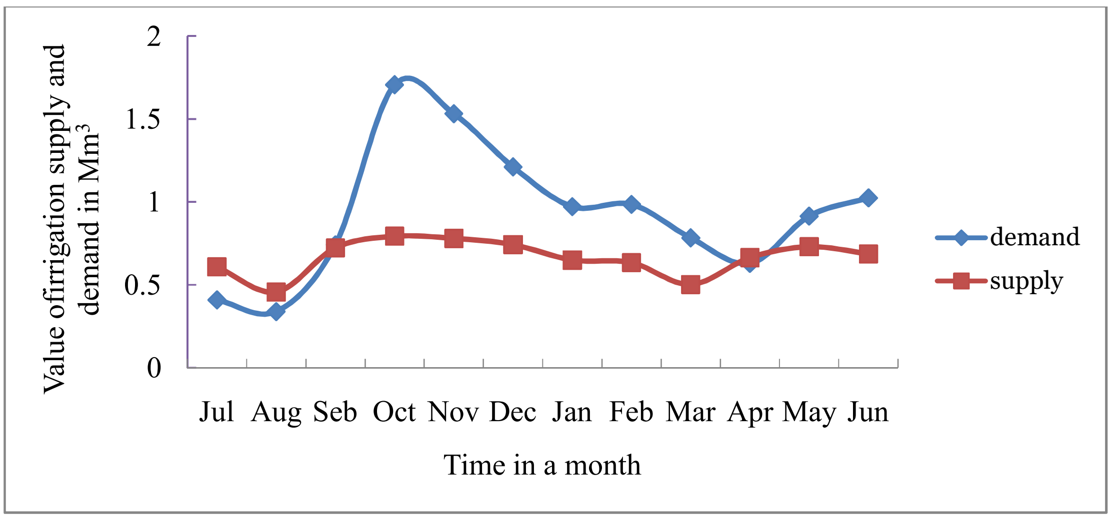

Figure 4.3 Total irrigation demand and supplied water for annual major crops

4.3. Current water productivity level under existing condition

Water productivity in this study was expressed in terms of the total available water (including both effective rain and diverted irrigation water), diverted irrigation water and water used by crop to evapotranspiration. Results of all water productivity values were expressed in physical (kg/m^3) and economic (ETB/m^3) as a net benefit terms, and their results are presented in Table 4.5, 4.6 and 4.7 respectively.

Value of physical and economic total water productivity of tomato, maize, dry beans and cotton were presented in table 4.5. Values of physical total water productivity of tomato, maize, dry beans and cotton were 4.32, 0.4, 0.14 and 0.25 kg/m^3 respectively. And value of economic total water productivity of tomato, maize, dry beans and cotton were 16.92, 0.58, 0.0 and 1.94 ETB/m^3 respectively. From table 4.5 it can be seen that for production year 2017/18 tomato production rate and economic productivity was higher than maize, dry beans and cotton per m^3 of total available water. On the other hand, net profit of dry beans was negative that means the production of dry bean cannot cover its production cost.

Table.4.5. Physical and economic total water productivity

crop	area Ha	Total yield Kg/total area	Total water Mm^3	Net profit M ETB	physical Wp Kg/m^3	economic Wp ETB/m^3
Tomato	213.27	9204846	2.131	36.050	4.32	16.92
Maize	88.8	526252	1.062	0.612	0.50	0.58
Dry beans	348.48	426906	3.000	-1.396	0.14	0.00
Cotton	518.35	1523739	6.185	12.024	0.25	1.94

Table.4.6. Physical and Economic diverted water productivity

crop	Area(ha)	Total yield (kg)	Diverted water(Mm^3)	Net profit (M ETB)	PWP (Kg/m^3)	EWP (ETB/m^3)
Tomato	223.02	9204846	1.664	36.050	5.53	21.66
Maize	88.8	526252	0.694	0.612	0.76	0.88
Dry beans	348.48	426906	2.351	-1.396	0.18	0.00
Cotton	518.35	1523739	3.425	12.024	0.44	3.51

In this case considering volume of water used for the competition of productivity was only the diverted water for each annual major crop in the production year. Values of physical and economic irrigation water productivity for annual major crops were presented in table 4.6. Physical irrigation water productivity of tomato, maize, dry beans and cotton were 5.53, 0.76, 0.18 and 0.44 kg/m^3; and economic productivity was 21.66, 0.88, 0.0 and 3.5 ETB/m^3 respectively. From table 4.6 it can be seen that for the production year 2017/18 physical and economic productivity of tomato using unit m^3 of irrigation water was higher than those other annual major crop grown in Nura Era irrigation scheme, and then it follows cotton and maize. The least productive in terms of physical and economic term was dry beans.

Physical and economic crop evaptranspirated water productivity value of annual major crops was presented in table 4.7. Physical and economic productivity of tomato, maize, dry beans and cottons from every meter cube of water lost through crop evapotranspiration were 7.57, 0.77, 0.25, 0.35 kg/m^3 and 29.66, 0.90, 0.0 and 2.80 ETB/m^3 respectively. Net economic return per unit of crop evapotranspiration was highest for tomato followed by cotton and the lowest was dry beans.

Table 4.7 physical and economic crop Evpotranspirated water productivity

crop	area (ha)	Total Yield(kg)	ETc (Mm^3)	Net Benefit (M ETB)	PWP (Kg/m^3)	EWP (ETB/m^3)
Tomato	213.02	9204846	1.216	36.050	7.57	29.66
Maize	88.8	526252	0.680	0.612	0.77	0.90
Dry beans	348.48	426906	1.707	-1.396	0.25	0.00
Cotton	518.35	1523739	4.301	12.0242	0.35	2.80
Total	**1168.65**	**11681743**	**7.903796**	**47.290**	**1.5**	**5.98**

Generally, tomato production were the highest in physical and economic productivity value from unit meter cube of total available, diverted irrigation water and crop evapotrasnpired water during growing season but dry bean was the least. Physical and economic productivity of tomato, maize, dry bean and cotton using a unit meter cube of irrigation (diverted) water were higher than using a unit meter cube of total available water. Physical and economic productivity of tomato, maize, and dry beans using a unit meter cube of crop evapotranspired water were higher than using total available and irrigation water. The result of physical crop water productivity of cotton in this study 0.35 kg/m^3 closer with (Ayana *et al*., 2015; Zwart and Bastiaanssen, 2004) but the result of maize 0.77kg/m^3 is very low compared to the finding of Zwart and Bastiaanssen, (2004). Even if the productivity of tomato in the scheme was higher but compared to the (Samia *et al*., 2018) is low.

4.4. Optimal cropping pattern and water productivity under different deficit CWR

In all proposed scenario, the nonlinear optimization model gives optimal cropping pattern and irrigation water requirement for annual crops without violating any constraints while satisfying maximum net profit. The results of the model for each scenario were summarizing in table below.

4.4.1. Scenario one (full CWR)

In this scenario, annual major crop uses full crop water requirement throughout growing season. Under such condition, results of the Non Linear Programming Model is summarized in table 4.8

Table.4.8 summary of optimization result of full irrigation scenario.

Crop	Optimized cropping pattern(ha)	optimized water demand(m^3/ha)	Total water demand(Mm^3)	Net profit (M ETB)	Economic WP (ETB/m^3)
tomato 1	120	8915.55	1.07	36.23	33.86
maize	0.00	0.00	0.00	0.00	0.00
dry bean1	123.16	6488.88	0.80	3.17	3.96
cotton	184.92	12484.44	2.31	5.39	2.33
tomato 2	93	15542.22	1.45	27.91	19.31
dry bean2	82.28	14377.77	1.18	1.34	1.14
Total	**603.36**	**57808.86**	**6.81**	**71.31**	**10.48**

According to the result in table 4.8, all crops have optimal cropping pattern except maize. The optimal cropping pattern of tomato1 and tomato 2 attain their maximum possible value set by factory capacity. In addition, they achieve maximum net profit and water productivity followed by dry bean1. Cotton have higher optimal cropping pattern due to this it use high amount of water compared to other. Furthermore, dry bean1 have higher optimal cropping pattern and water productivity next to cotton. Finally, this scenario produced a total net profit of 71.31 million ETB using cropping pattern and irrigation water of 603.36 ha and 6.81 million m^3 respectively. Therefore, the total economic water productivity of this scenario achieve 10.48 ETB/m^3

4.4.2. Scenario two (10% CWR deficit)

These scenario annual crops allowed using 10% CWR deficit throughout growing period. Under such condition, results of the Non Linear Programming Model are presented in Table 4.9.

Table 4.9 Summary result of scenario two

Crop	Optimized cropping pattern(ha)	Optimized water demand(m^3/ha)	Total water demand(Mm^3)	Net profit (M ETB)	Economic WP (ETB/m^3)
tomato 1	120	7654.63	0.92	32.06	34.90
maize	0.00	0.00	0.00	0.00	0.00
dry bean1	10.58	5762.34	0.06	0.23	3.80
cotton	141.43	10442.46	1.48	4.05	2.75
tomato 2	93	13773.36	1.28	24.10	18.82
dry bean2	207.71	12724.49	2.64	2.44	0.92
Total	**572.72**	**50357.28**	**6.38**	**63.21**	**9.91**

Optimal cropping pattern of tomato1, tomato2 and maize were remain the same as scenario one, Cropping pattern of dry bean1 and cotton were dropped to 10.58 and 141.43 ha from 123.16 and 184.92 ha (scenario1) respectively but dry bean 2 was raised to 207.71 ha (table 4.9). All crops have lower net profit than scenario one except dry bean2. This indicate that decrease in irrigation water application reduce the yield. Economic water productivity of tomato1 and cotton are raised compared to scenario one but drybean1, drybeans2 and tomato 2 were dropped, this show that crops those have higher irrigation water demand were low productive ,when their water demand decreased by 10%. Generally, a net profit of 63.21 million ETB and total economic water productivity of 9.91 ETB/m^3 obtained by utilizing a total cropping pattern of 572.72 ha and 6.38 M m^3 irrigation water. The total net profit and water productivity of this scenario is lower than scenario1 but it saves more irrigation water and cropping pattern.

4.4.3. Scenario three (20% CWR deficit)

This scenario allows annual crops to practice 20% CWR deficit over the total growing period. Under such condition, the result of the Non-Linear Programming Model is summarized in table 4.10

Table 4.10 Summary result of scenario three

Crop	Optimal cropping pattern(ha)	optimized water demand(m^3/ha)	total water demand(Mm^3)	net profit (M ETB)	economic WP (ETB/m^3)
tomato 1	213	6394.488	1.36	49.51	36.35
maize	0	0	0.00	0.00	0.00
dry bean1	0	0	0.00	0.00	0.00
cotton	187.18	8400.46	1.57	3.72	2.37
tomato 2	0	0	0.00	0.00	0.00
dry bean2	236.45	11071.15	2.62	1.69	0.65
Total	**636.63**		**5.55**	**54.94**	**9.90**

From table 4.10 it can be seen that optimal cropping pattern of tomato1 attain maximum possible value set by factory capacity constraints. In this, the area allocation of tomato 2 shifted to tomato1 because 20% CWR deficit reduce higher amount of yield in tomato2. This situation causes for reduction of total tomato yield and profit. Similarly, Cotton and drybean2 increased from 141.43, 207.71ha of (scenario two) to 187.18 and 236.45 ha respectively. On the other hand, optimal cropping pattern of dry beans1 and maize were zero. This shows that the deficit of CWR greater or equal to 20%, the yields of drybean1 was reduced and their profit was not competent with the tomato1, dry bean2 and cotton. The economic water productivity of tomato1 was rising from the former scenario to 36.35 ETB/m^3 but cotton and dry bean2 was dropped to 2.37 and 0.65 ETB/m^3 respectively.

Generally, a total net profit of 54.94 million ETB and total economic water productivity 9.90 ETB was attained by utilizing 636.63 ha of cropping pattern and 5.55 Mm^3 irrigation water. This scenario comparatively allocate higher cropping pattern and saving more water than the former scenarios but achieve lower net profit and water productivity.

4.4.4. Scenario four (30 % CWR deficit)

With application of 30 % deficit of crop water requirement of annual crop throughout growing period in the NLP optimization model, the result of the model summarized in Table 4.11

Table 4.11 summery result of scenario four

Crop	Optimized cropping pattern(ha)	optimized water demand(m^3/ha)	total water demand(Mm^3)	net profit (M ETB)	economic WP (ETB/m^3)
tomato 1	213	5239.13	1.12	42.73	38.29
maize	0.00	0.00	0.00	0.00	0.00
dry bean1	0.00	0.00	0.00	0.00	0.00
cotton	246.49	6782.284	1.67	4.00	2.39
tomato 2	0.00	0.00	0.00	0.00	0.00
dry bean2	274.43	9417.81	2.58	0.70	0.27
Total	**733.92**		**5.37**	**47.45**	**8.83**

From table 4.11 it can be seen that cropping pattern of cotton and drybean2 were still expanding from 187.18 and 236.45 ha (scenario 3) to 246.49 and 274.43 ha respectively. Nevertheless, their net profit and water productivity were decreasing. Furthermore, cropping pattern of tomato1 was remaining the same as scenario three. In addition, its economic water productivity was increased but net profit decreased compared to scenario3.

In general, this scenario achieves objective value of 47.45 M ETB and economic water productivity of 8.83 ETB/m^3 by utilizing cropping pattern of 733.92 ha and total irrigation water of 5.37 Mm^3. Therefore, this scenario irrigates larger area with lower irrigation water compared to the former scenarios but it generates lower net profit and water productivity.

4.4.5. Scenario five (40 % CWR deficit)

This scenario allows annual crops to use 40 % CWR deficit throughout growing seasons. Under such condition, the result of the Non Linear Programming Model were presenting in Table 4.12.

Optimal cropping pattern of tomato1 was remaining the same with former scenario; and the value is upper bound of tomato production for the case of factory capacity constraints. In addition cropping pattern of cotton increased to 325.77 ha but dry bean 2 drop to zero (table 4.12). This show that CWR of dry beans2 reduce by 40 % and above, yield reduction was high and the profit cannot competent with the remaining crops.

Table 4.12 summary result of scenario five

Crop	Optimized cropping pattern(ha)	optimized water demand(m^3/ha)	total water demand(Mm^3)	net profit (M ETB)	economic WP (ETB/m^3)
tomato 1	213	4199.67	0.89	36.63	40.95
maize	0.00	0.00	0.00	0.00	0.00
dry bean1	0.00	0.00	0.00	0.00	0.00
cotton	325.77	5333.98	1.74	4.22	2.43
tomato 2	0.00	0.00	0.00	0.00	0.00
dry bean2	0.00	0.00	0.00	0.00	0.00
Total	**538.77**		**2.63**	**40.85**	**15.52**

Moreover, Economic water productivity of tomato1 and cotton were increased compared to scenario 4. In addition to this net profit of cotton also increase; but tomato1 still decrease.

Generally, this scenario will generate 40.85 M ETB as a net profit and 15.52 ETB/m^3 as total economic water productivity by utilizing a total area of 538.77 ha and irrigation water of 2.63 Mm^3. Surprisingly this scenario rise the water productivity but its net profit less than former scenarios.

4.4.6. Scenario six (50 % CWR deficit)

This scenario allows annual crops to use 50 % CWR deficit over the total growing period in the developed optimization model. Under such condition, the result of the Non Linear Programming Model was summarized in Table 4.13

Table 4.13 summary result of scenario six

Crop	Optimized cropping pattern(ha)	optimized water demand(m^3/ha)	total water demand(Mm^3)	net profit (M ETB)	economic WP (ETB/m^3)
tomato 1	213	3464.17	0.74	32.31	43.79
maize	0.00	0.00	0.00	0.00	0.00
dry bean1	0.00	0.00	0.00	0.00	0.00
cotton	437.33	4054.244	1.77	4.39	2.48
tomato 2	0.00	0.00	0.00	0.00	0.00
dry bean2	0.00	0.00	0.00	0.00	0.00
Total	**650.33**	**7518.414**	**2.51**	**36.71**	**14.62**

When, CWR deficit reach to 50 % most of annual crops cannot fill the requirement of the model. This happen, due to crops having higher crop yield relation to water. For example optimal cropping pattern of tomato 2, maize and dry beans1 and dry bean 2 were zero and their net benefit and water productivity also nil. However, optimal cropping pattern of tomato1still at maximum allowed value 213 ha and cotton was 437.33 ha. And their economic water productivity was 43.79 and 2.48 ETB/m^3 respectively. Hence, in this scenario the model gives total net benefit of 36.71 M ETB and total economic water productivity of 14.62 ETB/m^3 using a total irrigation water of 2.51 Mm^3 and a total cropping pattern of 650.33 ha.

4.4.7. Comparison of existing and all optimized cropping pattern

As shown in figure 4.4 the total existing traditional cropping pattern reduced to different optimal cropping pattern due to constraints of irrigation water, cropping pattern, other constraints and due to requirement of maximum net profit trough this constrained resource. Those reduced optimal cropping patterns are numerically 603.36, 572.72, 636.63, 733.92, 538.77 and 650.33 ha by utilizing 0, 10, 20, 30, 40 and 50% CWR deficit scenario respectively. Also, as shown from the figure 4.4 total cropping pattern of existing condition greater than cropping pattern of all optimized scenario. Furthermore, cropping pattern of each crop in existing condition was greater than cropping pattern of each crop in all optimized scenarios (Table 4.8 to 4.13). This show that optimal cropping pattern of all crops was reduced from existing condition.

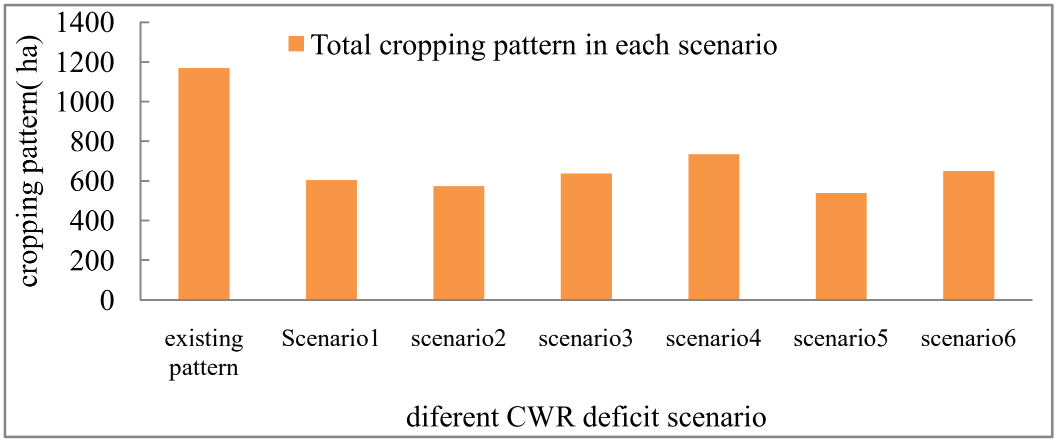

Figure 4.4 Total cropping patterns under existing and at different CWR scenario

Specially, maize could not allocate in any of the optimization scenarios. This is why the production and economic value of maize comparatively low. But cost of production and water demand rate is high. Due to this, the profit gained from maize cannot compete with those other crop in the model. Therefore, this situation supports the idea of (Kijne *et al*., 2003; Babazadeh *et al*., 2011). They stated that in choosing a crop the most important factor is economic net benefit gained in treatment, that have the maximum crop yield. Furthermore, dry bean 1 (produced in preseason) and tomato 2 (produced in post season) have no longer allocated when, the deficit of CWR greater than 20 %. This is due to having higher crop yield response to water.

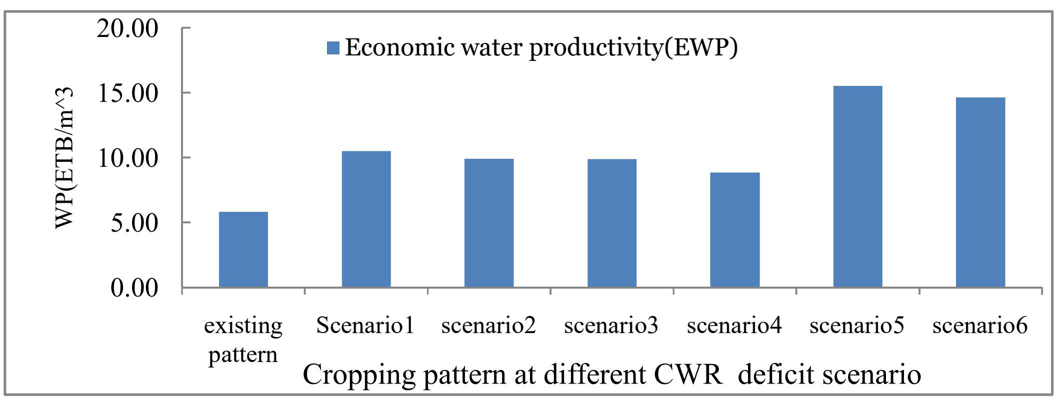

Figure 4.5 Total Economic water productivity of existing and all optimized cropping pattern

Moreover, the optimized cropping pattern increase the water productivity level of the schemes. As shown in figure 4.5, water productivity of optimal cropping pattern developed under 0, 10, 20, 30, 40 and 50% CWR deficit scenario was 10.48, 9.91, 9.90, and 8.83, 15.52 and 14.62 ETB/m^3 respectively. Therefore, those water productivity values improve the existing cropping pattern water productivity by 80.1, 70.3, 70.1, 51.8, 166.8 and 151.4 % respectively. Water productivity level of 40 % and 50 % CWR deficit scenario was very high but with regard to net profit, they were far from the optimal. While, water productivity level of full crop water requirement scenario was high next to 40 % and 50 % CWR deficit scenario.

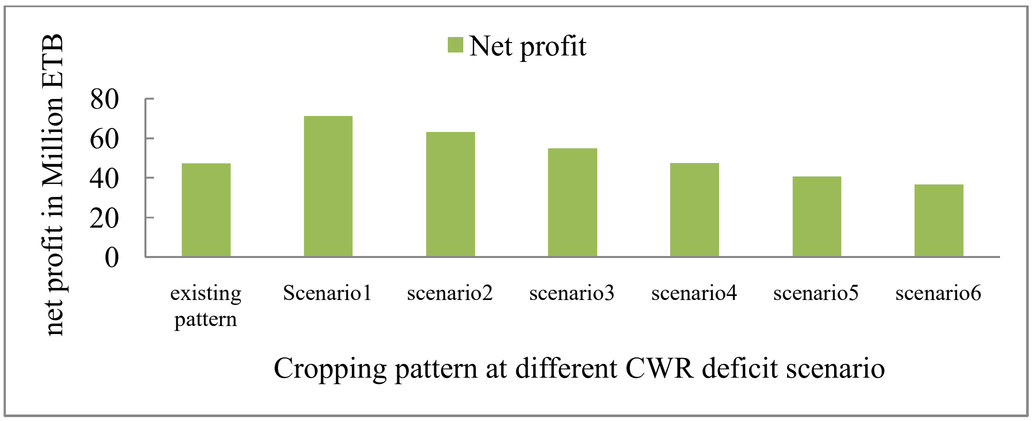

Figure 4.6 Total net profits under existing and all optimized cropping pattern

Furthermore, most of optimized cropping pattern also increase the net profit of the scheme. From figure 4.6 it can be seen that the net profit of optimal cropping pattern formulated in scenario1, 2, 3, and 4 observed as higher net profit than existing cropping pattern but scenario 5 and 6 were lower net profit. Therefore, those four preceding optimized cropping pattern improve the net profit of existing condition by 50.80, 33.66, 16.18, 0.33 % respectively. The maximum net profit was observed at full CWR and the minimum value was obtained at 50 % CWR deficit.

Generally, The finding from the model indicated that by allocating full CWR, 10, 20, 30, 40 and 50% CWR deficit, the overall net profit of the irrigation scheme can be increased to 71.31, 63.21, 54.94, 47.45, 40.85 and 36.71 M ETB, at optimal cropping pattern of 603.36, 572.72, 636.63, 733.92, 538.77 and 650.33 ha and water productivity of 10.81, 9.91, 9.9, 8.83, 15.52 and 14.62 ETB/m^3 respectively. Therefore, the combined highest net profit and Optimum water productivity was obtained at full crop water requirement scenario and it showed that an increase of 24.02 M ETB net profit and an increase of 4.66 ETB/m^3 water productivity as compared to the existing conditions. The finding of this study was similar to (Yonas, 2012 & Mahsafar *et al.*, 2017) with respect both net profit and water productivity improvement.

4.4.8. Sensitivity analysis of the model

When solving optimization problem with LINGO software, LINGO solution report, gives a reduced cost figure for each variable and a dual price figure for each constraint. This dual price (shadow price) of constraints is the rate of change of the optimal objective value with respect to a small change of right hand side of the constraints. And reduced cost report have two interpretation 1) For any non basic variable, the reduced cost for the variable is the amount by which its objective function coefficient must be improved before that variable will be a basic variable in some optimal solution and 2) the reduced cost of a variable may be interpreted as the amount of penalty would have to pay to introduce one unit of that variable into the solution. Hence, the reduced cost and dual price for the entire developed model were presented in appendix Table 19 and 20.

As show in appendix table 19, the reduced cost of variable (total water demand/ha and cropping pattern for each crops) are summarized for all scenario. For example the reduced cost of tomato2 implied that the objective function coefficient of scenario 3, 4, 5, and 6 must be improved by its respective value to be competitive in the model. The reduced cost of maize also implied that the objective function coefficient of all scenario improved by respective reduced cost value to be viable in the model. One meter cube of water will be used for maize in each scenario, the corresponding objective function value decreased by 0.003 units. Therefore, the objective coefficient ranges section of the lingo output gives the range of values for an objective function coefficient for which the current basis remains optimal were presented in appendix Table 21.

The LINGO solution report gives a dual price figure for each constraint. Dual price as the amount that the objective would improve as the right-hand side or constant term of the constraint is increased by one unit. Dual prices are sometimes called shadow prices, because they tell you how much you should be willing to pay for additional units of a resource. As shown in appendix table 20 Dual price of monthly available water from July to June was zero in all respective scenarios except in month of November, March and June.

This shows that extra water supply will not add any value to the objective function under the developed optimal cropping patterns and water allocation scenarios. However, the irrigation water availability in the month of November, March and June has positive dual prices in some scenario. For this reason, increase a unit of RHS constraint or increase one m^3 of water to the total monthly available Water in these months will increase the values of the objective function (net profit) by the corresponding values of the dual prices in each scenario. For example, increasing the available water in November by one unit will increase the net profit of Scenario1, Scenario2, Scenario3, Scenario4, Scenario 5 and Scenario 6 by 25.24, 23.93, 23.06, 21.56, 20.15 and 18.83 units respectively. Similarly in the month of March total monthly available water or RHS constraint increased by one unit the net profit also increased by 11.44, 9.28, 7.53 and 3.15 units for scenario 1, 2, 3, and 4 respectively. Total area of tomato was binding constraint, when increasing unit hectare of land for production of tomato in general on current RHS value; the objective function or net benefit of each scenario (i.e., scenario1, 2, 3, 4, 5, and 6) increased by 281396.5, 245701, 211981.4, 183909.7, 158616 and 141347.9 unit respectively. Total irrigation water demand per hectare for production of tomato1 and cotton has binding constraints in all scenarios. If one unit of HRS constraint or one m^3 of total water demand increasing in the respective scenario; the objective function value (net profit) increased by 3307 unit for scenario1and 2 and by 5870.27unit the rest of all scenario of tomato one. For cotton, the objective function (net profit) raised by 419.13, 515.05, 424.258, 738.34 and 991.21 unit for the respective scenario. Dual price for water demand per hectare of maize was zero in all scenarios. Increasing right hand side values infinitely cannot increase always the optimal value of the objective function at a rate specified by the dual prices, because they have range on the variations of the right hand side values over which the dual prices and reduced cost are kept constant under optimal condition. The allowable ranges on variations of the right hand side values (without changing the dual price and reduced cost) obtained from LINGO optimization software are shown in appendix Table 22 and 23.

4.3.8.1. Objective Coefficient Ranges

The objective coefficient ranges section of the lingo output gives the range of values for an objective function coefficient for which the current basis remains optimal. Within this range, the values of the decision variables remain unchanged, but the optimal objective value, dual prices and reduced cost, however may or may not change. Hence, the objective coefficients range for the entire optimization scenario presented in appendix Table 21. Allowable Increase (AI), tells us the amount that we could increase the objective coefficient without changing the optimal values for the variables. Allowable Decrease (AD) is the amount that the objective coefficient of the variable could decrease before the optimal values of the variables would change. For example, the optimal value of the decision variables will not change when the objective function coefficient of total water demand per hectare of tomato grown in pre season (water T1) is greater than current objective function coefficient in all scenario, and the optimal value of the decision variables will change when the objective function coefficient of cropping pattern of tomato1 grown in pre season (area T1) is less than current objective function coefficient in all scenario.

4.3.8.2. Right hand side Ranges report

If the right-hand side of a single constraint is changed within the range specified in the second section of the range report, then the optimal values of the dual prices and reduced costs will not change. However, the values of the decision variables and the objective function value may change. Allowable Increase and Allowable Decrease, tell us how far we can either increase or decrease the right-hand side coefficient of the row without causing a change in the optimal values of the dual prices or reduced costs. So, for example, the dual prices and reduced costs remain constant as long as the right hand side of row 3 (total available water July) appendix table 22 of scenario 1 greater than or equal to 118180.4 m^3.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Scarcity of water during critical irrigation period has intensified at Upper Awash Agro Industry Enterprise irrigation scheme. In addition, adoption of poor irrigation practice and fixed cropping pattern make the scheme low productive in terms of yield, profit and water. Therefore, to reduce this low productivity, propose optimizing cropping pattern and water productivity by aiming of net profit maximization and efficient utilization the scarce resource among the competing crops. To achieve this objective, irrigation water demand for the annual crops was determined using CROPWAT 8.0 model and the result compare with the actual supplied water. Physical and economic productivity of supplied water in terms of (total water, irrigation water and crop evapotranspirated water) were analyzed and finally nonlinear programming model was formulated using crop water production function to optimize cropping pattern and water productivity by allocating different crop water requirement. The objective function was net profit maximization equation as a function of crop production equation. While, the constraints are total land availability, monthly and annual irrigation water availability, investment cost and factory capacity constraints with a decision variable of cropping pattern and irrigation water demand of each crop. The program solved by lingo17.0 optimization software.

The study result show that the estimated water demand from month of July to September the available irrigation supply was meets the irrigation demand. On the other hand in the month of October, November and December the supplied water cannot meet above 45 % irrigation water demand of crops. This period was high amount of water demand season, because crop specially cotton and maize totally reach flowering, yield formation and ripening period. From January to March, the variation between supply and demand reduced compared to the former month. However, in the month of April supply meet the demand due to reduction of demand and availability of rainfall. Generally, the irrigation water demand of annual major crops of UAAIE irrigation scheme was higher than available water supply in the month of October to March and end of April to June. This finding has important implications for yield reduction.

Findings of water productivity of the study show that Physical and economic productivity of tomato, maize, dry beans and cotton using a unit meter cube of crop evapotranspired water were higher than using total available and irrigation water except cotton and it have higher irrigation water productivity compared to crop water productivity. Tomato production was the highest in physical and economic productivity value from using unit meter cube of total, irrigation and crop evapotrasnpired water, while dry bean was the least. On the other hand, the optimization model gives higher water productivity in all scenarios and higher net profit in scenario 1, 2, 3, and 4 compared to existing condition. Water productivity level of 40 and 50 % CWR deficit scenario was very high but with regard to net profit, they were far from the optimal. The optimal cropping pattern developed under full CWR scenario gave the maximum total profit as well as optimum water productivity compared to existing and all other scenarios. The total cropping patterns are reduced in all scenario compared to existing condition. This is due to limitation of available water. However, to irrigate the entire current cropping pattern, additional source of waters are required.

Recommendation

Based on the results obtained in this research the following important points are recommended.

- The current irrigation water management in the scheme was poor. Therefore, it needs improvement to achieve maximum profit and yield.
- To make the scheme profitable, it is advisable to use high value crops, which have low water requirement.
- The results from this study can be used as important inputs for scheme planner, decision makers and the owner in determining the cropping pattern for maximum net profit and water productivity under different water stress conditions.
- To use the model, scheme irrigation efficiency and water quality data should be checked and modified.
- To make the result of the model more reliable, experimental research with the same variable will be important.
- Further study will be required on perennial crops and the total scheme as a whole.

CHAPTER 6: REFERENCE

Adeba, D., Kansal, M., Sen, S., (2015). Assessment of water scarcity and its impacts on sustainable development in Awash basin, Ethiopia. *Sustain.*Water *Resour. Manag*.1:71–87. DOI 10.1007/s40899-015-0006-7

Ahmed M. Alabdulkader, Ahmed I. Al-Amoud, Fawzi S. Awad (2012).Optimization of the cropping pattern in Saudi Arabia using a mathematical programming sector model, Agric. Econ. – czEch, 58, (2): 56–60

Amare Shiberu Keraga, Zebene Kiflie and Agizew Nigussie Engida (2017). Evaluating water quality of Awash River using water quality index. *International Journal of Water Resources and Environmental Engineering*, Vol. 9(11), pp. 243-253, DOI: 10.5897/IJWREE2017.0736

Anuradha Sahoo and J. K. Dash (2016). A Novel Method for Optimal Solution of Fuzzy Chance Constraint Single-Period Inventory Model. *Advances in Fuzzy Systems* Volume 2016, Article ID 6132768,

Awash Basin Authority (AwBA) (2016).History of Awash basin authority. http://www.studiomaestro.nl/awba/awba/about-awba/.Accessed July16/2018.

Awash Basin Authority (AwBA) (2017). Strategic River Basin Plan for Awash Basin. Addis Ababa, Ethiopia.

Birhanu KT, Alamirew T, Olumana MD, Ayalew S, Aklog D (2015). Optimizing Cropping Pattern Using Chance Constraint Linear Programming for Koga Irrigation Dam, Ethiopia. *Irrigate Drainage Sys Eng*. 4: 134. doi:10.4172/2168-9768.1000134

Bruinsma J (2009). The Resource Outlook to 2050: By How Much do Land, Water and Crop Yields Need to Increase by 2050? Prepared for the FAO Expert Meeting on ‘How to Feed the World in 2050’, 24-26 June 2009, Rome

Daghighi, A., Nahvi, A., Kim, U., (2017). Optimal Cultivation Pattern to Increase Revenue and Reduce Water Use: Application of Linear Programming to Arjan Plain in Fars Province. *Agriculture*. 7, 73; doi:10.3390/agriculture7090073

Darshana, Ashish Pandey, Manfred Ostrowski and R. P. Pandey (2012). Simulation and Optimization for Irrigation and Crop Planning. Irrig. and Drain. 61: 178–188

Doorenbos, J. and A.H. Kassam, (1979). Yield response to water. *FAO Irrigation and Drainage* Paper No-33

English, M., (1990). Deficit irrigation. I. Analytical framework. J. Irrig. Drain E. ASCE 116, 399–412

FAO (1992). CROPWAT, a computer program for irrigation planning and management by M. Smith. *FAO Irrigation and Drainage Paper* No. 26. Rome.

FAO (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. By: Richard Allen,Luis Pereira, Dirk Raes and Martin Smith. *FAO Irrigation and Drainage Paper 56. Rome, Italy*

FAO(1985a). Water quality for agriculture. Irrigation and Drainage Paper 29, Rev. 1, FAO Rome, Italy

FAO. (1992). Crop water requirements By: Doorenbos and Pruitt. FAO Irrigation and Drainage Paper 24. Rome, Italy.

Gebremeskel Teklay & Mekonenn Ayana (2015). Evaluation of the effect of current irrigation water pricing system on water productivity in Awash River basin, Ethiopia. *Africa journal of agricultural research.*Vol 10(14), pp. 1789-1795.doi:10.5897/AJAR2013.7541

Goodarzi E, Ziaei M, Hosseinipour EZ (2014). Introduction to optimization analysis in hydrosystem Engineering. *Springer International Publishing,* Switzerland.

Hamid Mahsafar, Mohsen Najarchi, Mohammad Mahdi Najafizadeh and Mohammad Mirhoseini Hezaveh (2017). Optimal Allocation of Agriculture Water For Irrigation Of Multiple Crops Using Nonlinear Programming. *International Water Technology Journal, IWTJ Vol. 7–No.1,*

Hamid Mahsafar, Mohsen Najarchi, Mohammad Mahdi Najafizadeh and Mohammad Mirhoseini Hezaveh (2017). Conjunctive effect of water productivity and cultivation pattern on agricultural water management, *Water Science & Technology: Water Supply,* doi: 10.2166/ws.2017.054

Hamid Mahsafar, Mohsen Najarchi, Mohammad Mahdi Najafizadeh and Mohammad Mirhoseini hezaveh (2017). Optimal allocation of agriculture water for irrigation of multiple crops using nonlinear programming. *International Water Technology Journal, IWTJ* , Vol. 7–No.1

Hasan Symum & Mohammad F Ahmed (2015). Linear Programming Model to Optimize Water Supply and Cropping Area for Irrigation: A Case Study for Kalihati. *Global journal of researches in engineering*: vol 15 is 2 version1.0: online issn:2249-4596

Homayounfar M, Lai SH, Zomorodian M, Sepaskhah AR, Ganji A, (2014). Optimal Crop Water Allocation in Case of Drought Occurrence, Imposing Deficit Irrigation with Proportional Cutback Constraint. *Water Resources Management* 28: 3207-3225.

Kate A Brauman, Stefan Siebert and Jonathan A Foley (2013). Improvements in crop water productivity increase water sustainability and food security- a global analysis, *Environ. Res. Lett.* 8, 024030 (7pp) doi:10.1088/1748-9326/8/2/024030

La Zhuo and Arjen Y. Hoekstra (2017). The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint Front. *Agr. Sci. Eng*. 4(2): 185–194

M.H. Nazarifar, R. Momeni, M.H. Kanani and A.abolhasani (2017). Develop a non-linear optimization model for determining optimal cropping pattern under different water regimes *Academia Journal of Biotechnology* 5(9): 137-146, DOI: 10.15413/ajb.2017.0514

Mahtsente Tibebe & Birhanu Zemadim (2015).Water Demand Analysis and Irrigation Requirement for Major Crops at Holetta Catchment, Awash Subbasin, Ethiopia**.** *Journal of Natural Sciences Research*. Vol.5, No.15, ISSN 2224-3186 (Paper)

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M., Jacob Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management.*v l97, pp528–535

MoWR (Ministry of Water Resources) (2002). Water sector development program 2002-2012.*Main report volume* I. Addis Ababa, Ethiopia.

R. Shreedhar, Chandra Shekarayya G. Hiremath & Girish G.Shetty (2015). Optimization of Cropping pattern using Linear Programming Model for MarkandeyaCommand Area *International Journal of Scientific & Engineering Research*, Volume 6, Issue 9, ISSN 2229-5518

Reta Hailu, Degefa Tolossa and Getnet Alemu, (2017). Water security: stakeholders' arena in the Awash River Basin of Ethiopia. *Sustain. Water Resour.Manag*. DOI 10.1007/s40899-017-0208-2

Sam Geerts and Dirk Raes (2009). Review of Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*. 96, 1275–1284.

Samia M. El-Marsafawy , Atef Swelam and Ashraf Ghanem (2018). Evolution of Crop Water Productivity in the Nile Delta over Three Decades (1985–2015**).** *Water*, *10*, 1168; doi:10.3390/w10091168

Singh A (2012). Optimal allocation of resources for the maximization of net agricultural return. *Journal of Irrigation and Drainage Engineering* 138: 830-836.

Sisay B. Asres (2016). Evaluating and enhancing irrigation water management in the upper Blue Nile basin, Ethiopia: The case of Koga large scale irrigation scheme. *Agricultural Water Management.* 170 , 26–35

Tajin Kerim, Adane Abebe and Behailu Hussen, (2016). Study of Water Allocation for Existing and Future Demands under Changing Climate Condition: Case of Upper Awash Sub River Basin. *Journal of Environment and Earth Science*. Vol.6, ISSN 2224-3216 (Paper)

Wang LK & Yang CT (2014). Modern Water Resources Engineering *Humana Press*, New York.

WWAP (United Nations World Water Assessment Programme) (2014). The United Nations World Water Development Report 2014: *Water and Energy*. Paris, UNESCO.

WWAP (World Water Assessment Programme) (2012) United Nations World Water Development Report 4: Managing water under uncertainty and risk. Paris, UNESCO.

Yewendwosen Mamo1 and Zinabu Wolde (2015). Evaluation of Water Management in Irrigated Sugarcane Production: Case Study of Wondogenet, Snnpr, Ethiopia. *Global Advanced Research Journal of Physical and Applied Sciences* Vol. 4 (1) pp. 057-063,

Yonas Zeleke (2012).Optimizing water productivity and cropping pattern using linear programming model: a case study for amibara irrigation scheme in afar region, Ethiopia. *Unpublished MSc thesis*. Haramaya university

Z. Rabie, T. Honar, M. Mehdi Bateni, (2015). Determination of optimal and and water allocation under limited water resources using soil water balance in Ordibehesht canal of Doroodzan water district. *Iran Agricultural Research* (2015) 34(2) 21-28

Zeleke Agide Dejen (2015). Hydraulic and Operational Performance of Irrigation Schemes in View of Water Saving and Sustainability. UNESCO-IHE PhD thesis, ISBN 978-1-138-02767-1CRC Press/Balkema

Zwart, S.J. and Bastiaanssen, W.G.M., (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, 69(2), 115-133.

CHAPTER 7: APPENDIX

Table 1.Kc values for each growth stages of the considered annual crops.

Crop	Initial	Crop development	Mid-season	Late season
Bean-dry	0.4	-	1.15	0.35
Cotton	0.35	-	1.15	0.6
Maize-grain	0.3	-	1.2	0.6
Tomato	0.6	-	1.15	0.80

Source FAO,1998

Table 2.a. Approximate growth stages for the annual major crops.

Crop	Total	Initial	Crop dev't	Mid season	Late season
Dry beans	110	20	30	40	20
Cotton	195	30	50	65	50
Maize	180	30	50	60	40
Tomato	135	30	40	40	25

Source FAO,1998

Table 2.b. Ky value for each growth stage of considered annual crops

crop	initial	development	mid season	late season	total
Tomato	0.5	0.6	1.1	0.8	1.05
Maize	0.4	0.4	1.3	0.5	1.25
Dry beans	0.2	0.6	1	0.2	1.15
Cotton	0.2	0.5	0.5	0.25	0.85

Table3.Ranges of maximum effective depth (z_r), and soil water depletion fraction for no stress (p)

Crop	Maximum root depth(m)	Depletion fraction (for ET ≈ 5 mm/day)
Tomato	0.7- 1.5	0.4
Dry Beans	0.6-0.9	0.45
Maize	1.0-1.7	0.55
Cotton	1.0-1.7	0.65

Source FAO, 1998

Table 4 Crop tolerance and yield potential influenced by irrigation water salinity (ECw) or soil salinity (ECe)

Yield potential	100%		90%		75%		50%		0%	
crop	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw
Cotton(*Gossypiumhirsutum*)	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Corn(maize) *zeamays*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Tomato	2.5	1.7	3.5	2.3	5	3.4	7.6	5	13	8.4
Bean (Phaseolus vulgaris)	1	0.7	1.5	1	2.3	1.5	3.6	2.4	6.3	4.2

(Source FAO,1985a)

Table 5. Average monthly climate data of study area

Month	T max (^{0}C)	T min (^{0}C)	Humidity (%)	wind speed at 2m (m/s)	sunshine hour(hrs)	Rainfall (mm)
Jan	26.6	13.8	60.0	1.7	8.0	27.0
Feb	28.2	14.9	56.6	1.8	7.3	34.4
Mar	29.5	16.3	54.7	1.7	7.8	75.3
Apr	29.4	17.4	58.2	1.7	7.5	93.2
May	30.4	18.0	53.4	1.8	7.9	69.0
Jun	30.9	17.8	52.0	1.9	8.1	60.0
July	28.2	16.6	63.3	1.8	6.2	161.7
Aug	27.3	16.4	69.2	1.4	6.9	174.5
Sub	27.4	16.2	67.3	1.1	6.5	107.7
Oct	27.6	15.1	58.6	1.2	7.3	64.3
Nov	26.9	13.6	55.4	1.4	8.6	27.6
Dec	26.0	13.0	57.1	1.5	8.7	12.0

Table 6. Rain fall data and plotting position from 1988 – 2017

m	Jan	Feb.	mar	Apr	may	Jun	Jul	Aug	sub	Oct	Nov	Dec	Tr=(n+1)/m	p=1/Tr
1	189.9	347.4	186.1	339.3	152	126.4	290	285.4	218.7	234.4	126	68.8	31	0.03
2	108.8	148.2	170.2	204.2	143.4	121.1	275.9	280.9	197.7	229.6	110	50.1	15.5	0.06
3	67.7	69.6	165.8	183.5	142.6	117.1	249.6	221.5	193.8	165	108.7	39.3	10.33	0.10
4	66.5	67.2	162.4	151.2	140.8	106.6	243.7	214.3	179.2	158.7	66.8	33.8	7.75	0.13
5	52.7	58.2	147.8	146.3	130.1	101.3	220.9	211.4	144.8	153	65	32.1	6.20	0.16
6	46.6	50.3	144	123.2	121.7	90.3	220.8	206	140.6	143.1	48.6	25	5.17	0.19
7	40.5	50.2	130.3	119.2	102.8	82.4	217.9	204	135.9	120	47.9	20.9	4.43	0.23
8	37.8	40.9	119.3	114.6	100.3	79	210.3	200.6	130.3	116.8	45.8	8.1	3.88	0.26
9	34.8	38.8	102.9	112.3	85.9	73	208.5	192.4	125.5	93	45.1	7.6	3.44	0.29
10	33.8	38.3	100.2	106	85.5	70.6	193.9	185.1	124.5	86.6	19.7	6.6	3.10	0.32
11	27.5	32.4	90.1	104.9	82.8	69.8	182.8	181.9	120.7	59.6	14.5	6.4	2.82	0.35
12	25.8	24.5	79.5	103.8	82.8	63.2	174.3	176.6	119.5	58.6	14.1	5.8	2.58	0.39
13	19.9	22.4	78	93.6	82.7	57.4	171	176.4	106.9	49.1	13.9	5.2	2.38	0.42
14	16.8	18.2	76.7	88.1	72.5	57.3	159.2	175.8	103.3	40.7	13.7	5.2	2.21	0.45
15	9.4	7.3	74.4	83.6	71.1	56.2	152.3	175.6	102	34	10.6	4	2.07	0.48
16	7.5	5.9	71.5	80.1	67.1	51.8	148.75	172	99.5	24.4	8.8	3.7	1.94	0.52
17	7.4	3.4	61.4	76.2	64.2	51.7	147.8	169.7	97.3	22.5	8.1	1.7	1.82	0.55
18	5.4	2.4	61.2	74.6	58.3	50.5	142	167.8	95.5	21.7	7	0.2	1.72	0.58
19	4.8	2.4	49.3	62.7	47.4	49.9	136.7	157.4	92.8	21	7	0	1.63	0.61
20	3.6	2.1	44.1	62.2	45.2	48.8	133.5	156.9	85.7	19	4.7	0	1.55	0.65
21	2	1.3	38	56.3	40.8	42.1	121.8	154.6	85.3	17.8	3.5	0	1.48	0.68
22	0	0.5	33.6	47.4	28.7	39.9	119.4	154	81.9	16.4	3.1	0	1.41	0.71
23	0	0	31	46.9	28.4	38.2	118.3	140.2	77.4	13.9	2.9	0	1.35	0.74
24	0	0	10.6	45.3	22.4	37.2	108.6	135.8	76.7	11.4	1.7	0	1.29	0.77
25	0	0	10.5	38.4	21.8	31.3	107.9	132.7	76.3	8.3	1.4	0	1.24	0.81
26	0	0	9.3	37.2	18	22.4	106.6	129.8	66.2	5.5	1.1	0	1.19	0.84
27	0	0	5.6	36.3	15.4	22	94.4	128	54.5	3.8	0	0	1.15	0.87
28	0	0	3.1	27.3	12.1	19.7	72.5	125.2	52.3	1.85	0	0	1.11	0.90
29	0	0	1.1	26.3	1.8	13.4	65.6	115.8	46.1	0	0	0	1.07	0.94
30	0	0	0	4.6	0	9.6	56.7	107.2	0.925	0	0	0	1.03	0.97

Table7. Maximum yields and price of each annual crop,

Crop type	maximum yield kg/ha	Price in ETB/kg for 2017/18 year
Tomato	65000	6
maize	6000	5
Dry bean	2500	16
cotton	3300	16.5

Source: UAAIE crop planning and Finance department

Table 8.Coefficient of objective function value

crop	Tomato1	maize	Dry beans1	Cotton	Tomato2	Dry beans2
decision viriable	X1(ha) & IR(m3/ha/season)	X2(ha) & IR(m3/ha/season	X3(ha) & IR(m3/ha/season	X4(ha) & IR(m3/ha/season	X5(ha) & IR(m3/ha/season	X6(ha) & IR(m3/ha/season
(Pc)(ETB)	600	500	1600	1650	600	1600
Ym(Qunta)	650	60	25	33	650	25
(ky)	1.05	1.25	1.15	0.85	1.05	1.15
ER(m3/ha)	2704	2807	1811	3571	970	970
ETM(m3)	6685	8637	3934	9189	7964	7440
Cc(ETB/ha)	89820.45	22625	23503	25202	8920.45	23503
Wp(ETB/10^3m^3)	3	3	3	3	3	3
Sp(ETB/ha	84.1	84.1	84.1	84.1	84.1	84.1
η	0.45	0.45	0.45	0.45	0.45	0.45

Table 9 Yield and cost of production of annual major crops for production year 2017/18

Crop	Area (Ha)	Yield quintal	Machine 10^4ETB	Manual 10^4ETB	Seed 10^4ETB	Fertilizer 10^4ETB	Chemical 10^4ETB	Water&Water facility10^4ETB	Total 10^4ETB
Tomato	213.27	92048.46	79.74	596.30	624.40	136.28	478.87	2.29	1917.89
Maize	88.8	5262.52	24.87	114.84	8.15	40.47	12.57	0.96	201.87
DRY BEANS	348.48	4269.06	114.58	344.33	179.63	118.62	61.88	3.64	822.68
Cotton	518.35	15237.39	127.24	749.49	9.45	174.92	245.24	5.39	1311.74

Source UAAIE (crop department)

Table 10 effective rainfall, dependable and average rainfall and ETo

month	dep.Rainfall (mm)	Eff rain (mm)	Ave.Rainfall (mm)	ETo mm/day
Jan	0	0	27.0	4.05
Feb	0	0	34.4	4.44
Mar	10.5	10.3	75.3	4.90
Apr	38.4	36	93.2	4.86
May	21.8	21	69.0	5.12
June	31.3	29.7	60.0	5.25
July	107.9	89.3	161.7	4.34
Aug	132.7	104.5	174.5	4.16
Sep	76.3	67	107.7	4.00
Oct	8.3	8.2	64.3	4.17
Nov	1.4	1.4	27.6	4.20
Dec	0	0	12.0	3.98

Table 11 crop type and irrigation frequency of annual major crop

Crop type	Irrigation frequency	In date interval	Total irrigation period(month)
Tomato	17	8	$3\frac{1}{2}$ - $4\frac{1}{2}$
Maize	13	14	6
Dry bean	10	11	3- $3^1/_2$
Cotton	10	19	6

Table12 available irrigation water supply for annual major crops

Month	Tomato (10^3m^3)	Maize (10^3m^3)	Dry beans (10^3m^3)	Cotton (10^3m^3)	Total (10^3m^3)
Jul	94.3	42.0	-	471.7	608.1
Aug	55.7	81.6	20.4	471.7	629.4
Sub	64.0	102.3	84.4	471.7	722.5
Oct	100.5	102.3	117.6	471.7	792.2
Nov	100.5	102.3	291.1	285.4	779.3
Dec	116.4	102.3	407.0	115.9	741.5
Jan	171.6	80.4	396.9	-	648.9
Feb	183.1	60.2	389.4	-	632.8
Mar	178.6	20.7	302.0	-	501.3
Apr	179.4	-	216.0	267.9	663.3
May	231.6	-	100.0	397.2	728.9
Jun	188.7	-	25.7	471.7	686.1
Total	**1664.4**	**694.2**	**2350.6**	**3425.1**	**8134.3**

Table 12 Effective rainfall of annual crop in Mm^3 (eff. Rainfall (mm)*area of crop each month (ha)

month	Tomato Mm^3	Maize Mm^3	Dry bean Mm^3	Cotton Mm^3
Jul	0.117	0.052	0.000	0.740
Aug	0.030	0.089	0.016	0.654
Sub	0.022	0.072	0.043	0.419
Oct	0.035	0.070	0.059	0.411
Nov	0.001	0.001	0.003	0.005
Dec	0.032	0.042	0.121	0.060
Jan	0.000	0.000	0.000	0.000
Feb	0.029	0.019	0.090	0.000
Mar	0.094	0.022	0.234	0.000
Apr	0.046	0.000	0.060	0.129
May	0.022	0.000	0.014	0.095
Jun	0.039	0.000	0.008	0.247
Total	**0.467**	**0.368**	**0.650**	**2.760**

Table 13 Monthly irrigation requirement (IR) (mm) under Normal condition

Crops Month	Tomato IR.Req(mm)	Dry bean IR.Req(mm)	Maize IR.Req(mm)	cotton IR. Req(mm)
Jul	57.8	-	0	26.4
Aug	0.0	0	0	29.4
Sub	22.0	2.8	18.6	59.7
Oct	95.8	92.9	100.4	109.4
Nov	111.4	101.9	127.1	108.2
Dec	114.2	94.4	122.7	90.1
Jan	128.7	106.2	104.8	-
Feb	114.2	115.4	127.1	-
mar	134.8	121.8	76.6	-
Apr	86.9	95.0	-	21.1
may	115.0	119.7	-	50.3
Jun	119.8	88.8	-	67.2
Total	**1100.6**	**939.0**	**677.4**	**561.8**

Table 14 Monthly IR (mm) under 10% CWR deficit

Crops Month	Tomato	maize	dry bean	cotton
Jul	43.1	0.0	0.0	14.8
Aug	0.0	0.0	0.0	16.0
Sub	13.1	10.0	0.0	47.1
Oct	85.4	89.6	82.8	97.7
Nov	100.1	114.3	91.5	97.2
Dec	102.7	110.4	85.0	81.1
total	**344.5**	0.0	**259.3**	-
Jan	115.8	94.4	95.6	-
Feb	102.8	114.4	103.9	-
mar	120.3	67.9	108.6	-
Apr	74.6		81.9	15.4
may	101.4		105.6	43.2
Jun	104.8		77.0	57.5
total	**619.8**	**601.0**	**572.6**	**469.9**

Table 15 Monthly IR (mm) under 20% CWR deficit

Crops Month	Tomato	Maize	Dry beans	cotton
Jul	28.4	0.0		3.3
Aug	0.0	0.0	0.0	2.6
Sub	4.2	1.5	0.0	34.4
Oct	75.0	78.7	72.7	85.9
Nov	88.8	101.4	81.2	86.3
Dec	91.3	98.2	75.5	72.1
Total	**287.8**	-	**229.4**	-
Jan	102.9	83.9	85.0	-
Feb	91.4	101.7	92.4	-
mar	105.8	59.2	95.4	-
Apr	62.3	-	68.8	9.7
may	87.8	-	91.6	36.1
Jun	89.9	-	65.1	47.8
Total	**540.2**	**524.6**	**498.2**	**378.0**

Table 16 Monthly IR(mm) under 30% CWR deficit

Crops Month	Tomato	maize	Dry beans	cotton
Jul	13.7	0.0	-	0.0
Aug	0.0	0.0	0.0	0.0
Sub	0.0	0.0	0.0	21.7
Oct	64.6	67.8	62.6	74.1
Nov	77.5	88.6	70.9	75.3
Dec	79.9	85.9	66.1	63.1
Total	**235.8**	-	**199.5**	-
Jan	90.1	73.4	74.4	-
Feb	80.0	89.0	80.8	-
mar	91.3	50.5	82.2	-
Apr	50.0	-	55.7	4.0
may	74.2	-	77.5	28.9
Jun	74.9	-	53.3	38.1
Total	**460.5**	**455.2**	**423.8**	**305.2**

Table 17 Monthly IR(mm) under 40% CWR deficit

Crops Month	Tomato	maize	Dry bean	cotton
Jul	0	0		0
Aug	0	0	0	0
Sub	0	0	0	9.0
Oct	54.2	57.0	52.5	62.4
Nov	66.3	75.7	60.6	64.3
Dec	68.5	73.6	56.6	54.0
total	**189.0**	**-**	**169.7**	-
Jan	77.2	62.9	63.7	-
Feb	68.5	76.3	69.3	-
mar	76.8	41.8	69.0	-
Apr	37.7	-	42.6	0.0
may	60.6	-	63.4	21.8
Jun	60.0	-	41.4	28.4
Total	**380.9**	**387.3352**	**349.4**	**240.0292**

Table 18 Monthly IR (mm) under 50% CWR deficit

Crops Month	Tomato	maize	Dry beans	cotton
Jul	0	0	-	0
Aug	0	0	0	0
Sub	0	0	0	0
Oct	43.8	46.1	42.4	50.6
Nov	55.0	62.9	50.2	53.4
Dec	57.1	61.4	47.2	45.0
total	**155.9**	-	**139.8**	-
Jan	64.3	52.4	53.1	-
Feb	57.1	63.6	57.7	-
mar	62.3	33.2	55.8	-
Apr	25.5	-	29.5	0.0
may	47.0	-	49.3	14.7
Jun	45.0	-	29.6	18.7
Total	**301.2**	**319.5**	**275.0**	**182.441**

Table 19. Reduced cost of the variable

Crops	item	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6
Tomato planted in season one	water	0	0	0	0	0	0
	area	0	0	0	0	0	0
Tomato planted in Season Two	water	0	0	0.003	0.003	0.003	0.003
	area	0	0	279481.2	246316.5	218144.3	200876.1
Maize	water	0.003	0.003	0.003	0.003	0.003	0.003
	area	58864.33	51679.61	45872.57	38721.9	33275.94	29867.2
Dry bean planted in season one	water	0	0	0.003	0.003	0.003	0.003
	area	0	0	27141.96	23701.88	20622.64	17865.0
Dry bean planted in season two	water	0	0	0	0	0.003	0.003
	area	0	0	0	0	23589.80	23589.80
Cotton	water	0	0	0	0	0	0
	area	0	0	0	0	0	0

Table 20. Dual price of the NLP model for the entire scenario

item	scenario1	scenari2	scenario3	scenario4	scenaro5	scenario6
O.fun.	1	1	1	1	1	1
Total water	0	0	0	0	0	0
Jul	0	0	0	0	0	0
Aug	0	0	0			
sub	0	0	0	0		
Oct	0	0	0	0	0	0
Nov	25.24	23.933	23.067	21.566	20.15	18.832
Dec	0	0	0	0	0	0
Jan	0	0	0	0	0	0
Feb	0	0	0	0	0	0
mar	11.438	9.282	7.534	3.153	0	0
Apr	0	0	0	0	0	0
may	0	0	0	0	0	0
Jun	2.757	2.213	0	0	0	0
total area	0	0	0	0	0	0
factor	281396.5	245701.	211981.4	183909.7	158616	141347.9
tomato1	3307	3307	5870.277	5870.277	5870.27	5870.277
maize	0	0	0	0	0	0
dry bean 1	87.32	55.65	0	0	0	0
cotton	419.13	515.05	424.258	558.68	738.34	991.21
tomato2	2152.01	2152.01	0	0	0	0
drybeans2	228.73	291.05	657.34	762.90	0	0
Invn't cost	0	0	0	0	0	0

note: as shown in the above table ofun, represents objective function , total water total available water and name indicated by months are represents available supplied water in each month and item represent by each crop name was irrigation water demand (m3/ha)/year at the end investment cost for each crop

Table 21. objective coefficient range of each scenario

Variable	current coefficient	scenario1		scenario 2		scenario3		scenario 4		scenario5		scenario6	
		AI	AD	AI	AD	AI	AD	AI	AD	AI	AD	AI	AD
area of t1	Nonlinear	∞	0	∞	0	∞	0	∞	0	∞	0	∞	0
Water of t1	Nonlinear	∞	0	∞	0	∞	0	∞	0	∞	0	∞	0
area of maize	Nonlinear	0	∞	0	∞	0	∞	0	∞	0	∞	0	∞
water of maize	Nonlinear	0	∞	0	∞	0	∞	0	∞	0	∞	0	∞
area of drybeans1	Nonlinear	0	0	0	0	0	∞	0	∞	0	∞	0	∞
water of drybeans1	Nonlinear	∞	0	∞	0	0	∞	0	∞	0	∞	0	∞
area of cotton	Nonlinear	0	0	0	0	0	0	0	0	0	0	0	0
water of cotton	Nonlinear	∞	0	∞	0	∞	0	∞	0	∞	0	∞	0
area of t2	Nonlinear	0	0	0	0	0	∞	0	∞	0	∞	0	∞
water of t2	Nonlinear	∞	0	∞	0	0	∞	0	∞	0	∞	0	∞
area of drybeans2	Nonlinear	0	0	0	0	0	∞	0	∞	0	∞	0	∞
water of drybeans2	Nonlinear	∞	0	∞	0	0	∞	0	∞	0	∞	0	∞

Appendix table 24. Planting data and planted area of annual crops

crop type	planting dat	area(Ha)	crop type	planting dat	area(Ha)	crop type	planting dat	area(Ha)
tomato	15/7/17	6.5	cotton	02/04/17	47.5	d beans	17/8/17	13
t0mato	11/09/17	9.51	cotton	13/4/17	59.5	d.beans	12/09/17	32.2
tomato	01/12/17	12.5	cotton	20/4/17	40	d beans	01/11/17	30
tomato	12/01/18	12.65	cotton	27/4/17	35.5	d. beans	10/11/17	25.6
tomato	04/03/18	17.33	cotton	02/05/17	21.2	d. beans	22/11/17	24.9
Tomato	03/03/18	5.42	cotton	05-Dec	28.05	d. beans	27/12/17	66.34
Tomato	01/04/18	4.45	cotton	17/5/17	16.45	d. beans	22/1/18	47.27
Tomato	17/4/18	5.3	cotton	24/5/17	20.62	d.beans	20/2/18	16.34
Tomato	20/2/18	5	cotton	30/5/17	24.83	beans	17/12/17	7.4
Tomato	03/08/17	14.42	cotton	10/06/17	17.85	D beans	20/11/17	17.3
Tomato	24/12/17	8	cotton	16/6/17	30.43	D beans	03/09/17	8.5
Tomato	17/1/18	8.89	cotton	20/6/2017	33.57	D beans	02/10/17	21.1
Tomato	28/10/17	9.2	cotton	31/3/18	42.58	Dbeans	30/11/2017	12.5
Tomato	12/10/17	3		10/04/18	33.54	Maize	01/07/01	19
Tomato	20/9/17	3.85	cotton	04/04/17	22.23	maize	22/7/2017	17.5
Tomato	02/10/17	3.65	cotton	22/04/17	89.62	maize	23/8/2017	34.3
Tomato	31/12/17	3.21	cotton	15/5/2017	31	maize	27/9/2017	18

Table 22. Allowable range of RHS constraints

	current	scenario1		scenario 2		scenario3		scenario 4AI		scenario5		scenario6	
Variable	RHS	AI	AD	AI	AD	AI	AD		AD	AI	AD	AI	AD
yearly	Nonlinea	0	0	0	0	0	0	0	0	0	0	0	0
July	273656.4	∞	155476	∞	188303	∞	206987	∞	244475				
Aug	283244.2	∞	228876	∞	246884	∞	278377						
sub	325118.2	∞	187852	∞	202364	∞	251779	∞	271629	∞	295799		
Oct	356482.2	∞	23789.4	∞	23218.3	∞	35938	∞	36230	∞	37758	∞	41896
Nov	350687.9	0	0	0	0	0	0	0	0	0	0	0	0
Dec	333690.8	∞	14359.7	∞	17157.9	∞	4258.7	∞	7963.6	∞	11871	∞	15266
Jan	291993.8	∞	84921.6	∞	84209.6	∞	91005	∞	87818	∞	291993	∞	291993
Feb	284737.6	∞	83580.6	∞	80352.8	∞	66251	∞	62999	∞	28737	∞	284737
mar	225580.9	0	0	0	0	∞	0	∞	0	∞	225580	∞	225580
Apr	298484.0	∞	100482	∞	108363	∞	117644	∞	135768	∞	298484	∞	298484
may	328003.4	∞	29546.5	∞	24969.3	∞	43834	∞	44084	∞	256986	∞	263715
Jun	308749.0	0	0	0	0	∞	65340	∞	68564	∞	216231	∞	131117
Total.a	1170.0	∞	673.19	∞	614.47	∞	533.36	∞	436.07	∞	631.23	∞	519.66
Fac. cap	213.0	0	0	0	0	0	0	0	0	0	0	0	0
cost	42541770	∞	1.6E+07	∞	1.5E+07	∞	1E+07	∞	1E+07	∞	2E+07	∞	1E+07

Table 23 Allowable RHS range of yearly water demand per hectare for each scenario

Variable		water demand of tomato1	water demand of maize	water demand of drybean2	water demand of cotton	water demand of tomato2	water demand of drybeans2
current RHS		8915.55	15053.33	6488.88	12484.44	15542.2	14377.77
	AI	0	∞	0	0	0	0
scenario1	AD	0	15053.33	0	0	0	0
current RHS		7654.632	13355.4	5762.34	10442.4	13773.3	12724.49
	AI	0	∞	0	0	0	0
scenario 2	AD	0	13355.4	0	0	0	0
current RHS		6394.488	11656.9	5098.376	8400.45	12003.4	11071.15
	AI	0	∞	∞	0	∞	∞
scenario3	AD	0	11656.9	5098.376	0	12003.4	0
current RHS		5239.136	10115.7	4434.412	6782.28	10233.6	9417.812
	AI	0	∞	∞	0	∞	∞
scenario 4	AD	0	10115.7	4434.412	0	10233.6	0
current RHS		4199.67	8607.44	3770.449	5333.98	8463.72	7764.47
	AI	0	∞	∞	0	∞	∞
scenario5	AD	0	8607.44	3770.449	0	8463.72	7764.47
current RHS		3464.17	7099.17	3106.485	4054.24	6693.84	6111.136
	AI	0	∞	∞	0	∞	∞
scenario6	AD	0	7099.17	7099.17	0	6693.84	6111.136

Appendix for Model solution report

@ Full CWR

Local optimal solution found.

Objective value:	0.7131225E+08
Infeasibilities:	0.000000
Extended solver steps:	10
Best multistart solution found at step:	1
Total solver iterations:	69
Elapsed runtime seconds:	1.28
Model Class:	NLP
Total variables:	12
Nonlinear variables:	12
Integer variables:	0
Total constraints:	24
Nonlinear constraints:	2
Total nonzeros:	82
Nonlinear nonzeros:	24

Variable	Value	Reduced Cost
R1	8915.550	0.000000
X1	120.0000	0.000000
R5	15542.22	0.000000
X5	93.00000	0.000000
R2	0.000000	0.3000000E-02
X2	0.000000	58864.33
R3	6488.880	0.000000
X3	16.60222	0.000000
R6	14377.77	0.000000
X6	82.27989	0.000000
R4	12484.44	0.000000
X4	184.9263	0.000000

Row	Slack or Surplus	Dual Price
1	0.7131225E+08	1.000000
2	2019560.	0.000000
3	155475.9	0.000000
4	228875.9	0.000000
5	187852.3	0.000000
6	23789.38	0.000000
7	0.000000	25.24073
8	14359.72	0.000000
9	84921.56	0.000000
10	83580.61	0.000000
11	0.000000	11.43818
12	100481.7	0.000000
13	29546.46	0.000000
14	0.000000	2.757539
15	673.1916	0.000000
16	0.000000	281396.5
17	0.000000	3307.197
18	15053.33	0.000000
29	0.000000	87.32468
20	0.000000	419.1324
21	0.000000	2152.017
22	0.000000	228.7351
23	0.1642543E+08	0.000000

@10% CWR deficit

Local optimal solution found.
Objective value: 0.6320878E+08
Infeasibilities: 0.000000
Extended solver steps: 10
Best multistart solution found at step: 1
Total solver iterations: 70
Elapsed runtime seconds: 0.58

Model Class: NLP

Total variables: 12
Nonlinear variables: 12
Integer variables: 0

Total constraints: 24
Nonlinear constraints: 2

Total nonzeros: 81
Nonlinear nonzeros: 24

Variable	Value	Reduced Cost
R1	7654.632	0.000000
X1	120.0000	0.000000
R5	13773.36	0.000000
X5	93.00000	0.000000
R2	0.000000	0.3000000E-02
X2	0.000000	51679.61
R3	5762.340	0.000000
X3	10.58122	0.000000
R6	12724.49	0.000000
X6	104.6971	0.000000
R4	10442.46	0.000000
X4	141.4292	0.000000

Row	Slack or Surplus	Dual Price
1	0.6320878E+08	1.000000
2	2168578.	0.000000
3	188303.1	0.000000
4	246884.1	0.000000
5	202363.6	0.000000
6	23218.32	0.000000
7	0.000000	23.93301
8	17157.89	0.000000
9	84209.62	0.000000
10	80352.76	0.000000
11	0.000000	9.281977
12	108362.7	0.000000
13	24969.27	0.000000
14	0.000000	2.213054
15	614.4726	0.000000
16	0.000000	245701.7
17	0.000000	3307.197
18	13355.44	0.000000
19	0.000000	55.65420
20	0.000000	515.0572
21	0.000000	2152.017
22	0.000000	291.0548
23	0.1497344E+08	0.000000

@20%CWR deficit scenario

Local optimal solution found.
Objective value: 0.5494105E+08
Infeasibilities: 0.000000
Extended solver steps: 10
Best multistart solution found at step: 1
Total solver iterations: 68
Elapsed runtime seconds: 0.59

Model Class: NLP

Total variables: 12
Nonlinear variables: 12
Integer variables: 0

Total constraints: 24
Nonlinear constraints: 2

Total nonzeros: 81
Nonlinear nonzeros: 24

Variable	Value	Reduced Cost
R1	6394.488	0.000000
X1	213.0000	0.000000
R5	0.000000	0.3000000E-02
X5	0.000000	279481.2
R2	0.000000	0.3000000E-02
X2	0.000000	45872.57
R3	0.000000	0.3000000E-02
X3	0.000000	27141.96
R6	11071.15	0.000000
X6	236.4570	0.000000
R4	8400.458	0.000000
X4	187.1877	0.000000

Row	Slack or Surplus	Dual Price
1	0.5494105E+08	1.000000
2	2581945.	0.000000
3	206986.8	0.000000
4	278377.1	0.000000
5	251779.4	0.000000
6	35937.75	0.000000
7	0.000000	23.06744
8	4258.656	0.000000
9	91004.53	0.000000
10	66250.71	0.000000
11	0.000000	7.534589
12	117644.4	0.000000
13	43833.60	0.000000
14	65339.75	0.000000
15	533.3553	0.000000
16	0.000000	211981.4
17	0.000000	5870.277
18	11656.94	0.000000
19	5098.376	0.000000
20	0.000000	424.2580
21	12003.48	0.000000
22	0.000000	657.3475
23	0.1313498E+08	0.000000

@ 30% CWR deficit Scenario

Local optimal solution found.
Objective value: 0.4744704E+08
Infeasibilities: 0.000000
Extended solver steps: 10
Best multistart solution found at step: 1
Total solver iterations: 68
Elapsed runtime seconds: 0.58

Model Class: NLP

Total variables: 12
Nonlinear variables: 12
Integer variables: 0

Total constraints: 23
Nonlinear constraints: 2

Total nonzeros: 77
Nonlinear nonzeros: 24

Variable	Value	Reduced Cost
R1	5239.136	0.000000
X1	213.0000	0.000000
R5	0.000000	0.3000000E-02
X5	0.000000	246316.5
R2	0.000000	0.3000000E-02
X2	0.000000	38721.90
R3	0.000000	0.3000000E-02
X3	0.000000	23701.88
R6	9417.812	0.000000
X6	274.4282	0.000000
R4	6782.284	0.000000
X4	246.4967	0.000000

Row	Slack or Surplus	Dual Price
1	0.4744704E+08	1.000000
2	2762025.	0.000000
3	244475.0	0.000000
4	271628.2	0.000000
5	36229.96	0.000000
6	0.000000	21.56654
7	7963.595	0.000000
8	87818.40	0.000000
9	62999.00	0.000000
10	0.000000	3.152942
11	135767.6	0.000000
12	44083.59	0.000000
13	68563.52	0.000000
14	436.0751	0.000000
15	0.000000	183909.7
16	0.000000	5870.277
17	10115.73	0.000000
18	4434.412	0.000000
19	0.000000	558.6817
20	10233.60	0.000000
21	0.000000	762.9075
22	0.1074782E+08	0.000000

@ 40% CWR deficit scenario

Local optimal solution found.
Objective value: 0.4085185E+08
Infeasibilities: 0.000000
Extended solver steps: 10
Best multistart solution found at step: 1
Total solver iterations: 68
Elapsed runtime seconds: 0.56

Model Class: NLP

Total variables: 12
Nonlinear variables: 12
Integer variables: 0

Total constraints: 22
Nonlinear constraints: 2

Total nonzeros: 75
Nonlinear nonzeros: 24

Variable	Value	Reduced Cost
R1	4199.671	0.000000
X1	213.0000	0.000000
R5	0.000000	0.3000000E-02
X5	0.000000	218144.3
R2	0.000000	0.3000000E-02
X2	0.000000	33275.94
R3	0.000000	0.3000000E-02
X3	0.000000	20622.64
R6	0.000000	0.3000000E-02
X6	0.000000	23589.80
R4	5333.982	0.000000
X4	325.7667	0.000000

Row	Slack or Surplus	Dual Price
1	0.4085185E+08	1.000000
2	5502121.	0.000000
3	295799.0	0.000000
4	37757.57	0.000000
5	0.000000	20.15090
6	11870.97	0.000000
7	291993.0	0.000000
8	28737.00	0.000000
9	225580.0	0.000000
10	298484.0	0.000000
11	256985.9	0.000000
12	216231.3	0.000000
13	631.2333	0.000000
14	0.000000	158616.0
15	0.000000	5870.277
16	8607.448	0.000000
17	3770.449	0.000000
18	0.000000	738.3473
19	8463.719	0.000000
20	7764.474	0.000000
21	0.1519999E+08	0.000000

@50% CWR deficit Scenario

Local optimal solution found.
Objective value: 0.3671135E+08
Infeasibilities: 0.000000
Extended solver steps: 10
Best multistart solution found at step: 1
Total solver iterations: 67
Elapsed runtime seconds: 0.56

Model Class: NLP

Total variables: 12
Nonlinear variables: 12
Integer variables: 0

Total constraints: 21
Nonlinear constraints: 2

Total nonzeros: 74
Nonlinear nonzeros: 24

Variable	Value	Reduced Cost
R1	3464.170	0.000000
X1	213.0000	0.000000
R5	0.000000	0.3000000E-02
X5	0.000000	200876.1
R2	0.000000	0.3000000E-02
X2	0.000000	29867.29
R3	0.000000	0.3000000E-02
X3	0.000000	17865.07
R6	0.000000	0.3000000E-02
X6	0.000000	23589.80
R4	4054.244	0.000000
X4	437.3352	0.000000

Row	Slack or Surplus	Dual Price
1	0.3671135E+08	1.000000
2	5623353.	0.000000
3	41896.39	0.000000
4	0.000000	18.83240
5	15266.16	0.000000
6	291993.0	0.000000
7	284737.0	0.000000
8	225580.0	0.000000
9	298484.0	0.000000
10	263715.1	0.000000
11	131117.3	0.000000
12	519.6648	0.000000
13	0.000000	141347.9
14	0.000000	5870.277
15	7099.170	0.000000
16	3106.485	0.000000
17	0.000000	991.2172
18	6693.840	0.000000
19	6111.136	0.000000
20	0.1238823E+08	0.000000