Birhanu et al., Irrigat Drainage Sys Eng 2015, 4:2
DOI: 10.4172/2168-9768.1000134

Irrigation & Drainage Systems Engineering

Research Article Open Access

Optimizing Cropping Pattern Using Chance Constraint Linear Programming for Koga Irrigation Dam, Ethiopia

Kassahun Tadesse Birhanu*, Tena Alamirew, Megerssa Dinka Olumana, Semu Ayalew and Dagnachew Aklog

Natural Resources Management, Debre Markos University, Ethiopia

Abstract

Optimal cropping pattern decisions without consideration to water supply uncertainty would result in yield/benefit that is less than expected and probability of system failure in meeting a given irrigation demand. In this study, a chance constraint linear programming (CCLP) model was used for optimizing cropping pattern for major crops grown at Koga Irrigation scheme, Ethiopia. The model incorporated uncertainty of inflow at exceedance probability of 90%, 80%, 70%, 60% and 50%. The model objectives were yield and benefit maximizations subject to land and water availability constraints. Each objective function has four scenarios. The models were solved using LINGO14. 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. In conclusion, the irrigated land in 2012/13 was below the optimal value and the irrigation water was mismanaged. Therefore, with optimal crop planning and water management, the design command area of 7000 ha could be irrigated. Finally, a study should be made to determine optimal levels of crop water deficit that maximize water productivity.

Keywords: Cropping pattern; Exceedance probability; LINGO; Optimization

Introduction

The world's readily available fresh water resources are becoming 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 [1]. Irrigation accounts for 70% of total freshwater withdrawals globally, with the industrial and domestic sectors accounting for the remaining 20% and 10%, respectively [2]. With expected increases in population by 2030, food demand is predicted to increase by 50% (70% by 2050) [3]. Without improved efficiencies, agricultural water consumption is expected to increase by about 20% globally by 2050 [4]. Irrigation accounts for more than 40% of the world's production on less than 20% of the cultivated land [4]. 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 [4]. 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 [5]. Water scarcity and decreasing availability of water for agriculture constrain irrigated production overall, and particularly in the most hydrologically stressed areas and countries [2]. These call for increasing production per unit area and per unit water. However this needs more scientific utilization of the water resources and their optimal allocation to achieve maximum returns. Improving the irrigation efficiency, revising crop patterns, and optimizing water allocation [5]. Optimal irrigation system planning and operation are amongst many measures. The success of irrigation system operation and planning depends on the quantification of supply and demand and equitable distribution of supply to meet the demand if possible, or, to minimize the gap between the supply and demand [6]. For this purpose, optimization models are required to select optimal solutions, systematically, under agreed-upon objectives and constraints [7].

Ethiopia has vast cultivable land of 30 to 70 M ha, but only 15 M ha of land is under cultivation, with current irrigation schemes covering about 640,000 ha out 5.3 M ha of total potential irrigable land [8]. In Ethiopia, due to lack of water storage infrastructure and large spatial and temporal variations in rainfall, there is not enough water for most farmers to produce more than one crop per year [8]. Hence, Ethiopia is increasingly investing in irrigation sector in order to exploit the agricultural production potential of the country: (i) to achieve food self sufficiency at the national level, (ii) to generate foreign currency from export earnings, and (iii) satisfy the raw material demand of local industries [9]. One of the investments is Koga Dam and Irrigation Scheme located south of Lake Tana, in the Upper Blue Nile Basin. The scheme was designed to irrigate 7000 ha command areas [10]. According to MacDonald [10], the potential irrigable area is 7572 ha. However, the maximum actual irrigated area was 5123 ha in 2011/12 and 5144.36 ha in 2012/13. This is 73.5% of the design command areas. This implies that either the reservoir water was mismanaged or too small to irrigate design command areas. Multiple cropping patterns are also the common practice at Koga and other irrigation schemes in Ethiopia. An economically efficient cropping pattern defines the optimal crop area and water allocation for seasonal, annual and perennial crops, subject to constraints on land and water availability [11]. The cropping pattern of Koga Irrigation Scheme varies year to year depending upon farmers' preferences, socioeconomic factors and government directives. This affects the amount and timing of irrigation water demand, the size of cropping area, the yield /benefit,

---

***Corresponding author:** Kassahun Tadesse Birhanu, Professor, Natural Resources Management, Debre Markos University, Ethiopia, Tel: +251587716691; E-mail: kbirhan@gmail.com

Received March 15, 2014; **Accepted** April 07, 2015; **Published** April 11, 2015

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

and reservoir operation policy. Irrigation managers and/or decision makers always face a problem of optimally allocating available land water resources to multiple crops at the beginning of every irrigation season to maximize the yield or benefit from irrigation projects. Under these circumstances, optimization techniques are required to balance water supply and demands of multiple crops. Among the available optimization techniques such as Linear Programming (LP), Dynamic Programming (DP) and Genetic Algorithm (GA), it is LP model that is more popular because of the proportionate characteristic of the allocation problems [12]. Moreover, LP model can handle a large number of constraints and thus, are an effective tool to aid in the optimization process [13]. Linear programming based optimization methods are popularly used to derive the policies and are found as an effective tool in dealing with the allocation of resources during irrigation planning [14]. The LP is also easy to apply with the problem of irrigation planning using several available programs [15]. However, neither of optimization approaches was used to define optimal cropping patterns during designing nor operation phase of Koga irrigation project. Moreover, none of optimization methods to date has been widely adopted in irrigation sector, Ethiopia. Nevertheless, in the past years, various optimization methods have been used in irrigated agriculture world-wide to define optimal cropping patterns. However, no single optimization method or algorithm can be applied efficiently to all problems [16]. The Linear programming (LP) model developed to select the optimal cropping patterns in, Zimbabwe were found to be more superior to traditional methods in maximizing profit while achieving other goals such as food security [17]. LP models were also used to improve annual benefits in multi objective crop planning [18]. A linear programming model was used to maximize the total gross margin for the delivery of water to agricultural areas that cover an irrigation network over a planning horizon in Iran [19]. A weekly LP model was formulated for determining the optimal cropping pattern and reservoir water allocation for an existing storage based irrigation system in India [20]. LP model based on simplex method was used for optimal utilization of water and land resources [21]. A linear programming model was developed for the optimal land and water resources allocation to maximize net annual returns from a command area [12]. Multiregional LP model was applied for managing cropping patterns of agricultural crops in Iran [22]. LP model was used for optimization of irrigation water management in Pakistan [23]. A Linear programming technique was applied to determine the optimum land allocation to 10 major crops in India [24]. Uncertainty is always an important factor that affects the management of an agricultural water resources system owing to the existence of spatial and temporal variations [25]. Two possible results of decisions without consideration to uncertainty are the creation of a net benefit that is less than expected and probability of system failure in meeting a given demand or other system constraint [26]. For this reason, the application of chance constraint programming that considers uncertainty of reservoir inflow for optimizing cropping pattern is imperative. This study was conducted with the objectives of finding optimal cropping patterns for yield and benefit maximizations. Therefore, 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 out of the stored and incoming water during irrigation season.

Material and Methods

Description of the study area

The study area is Koga Irrigation scheme located south of Lake Tana in the Upper Blue Nile River Basin, Ethiopia (Figure 1). The Koga catchment lies in the Tana Basin between 11°10’ and 11°22’ North Latitude and 37°02’ and 37°17’ East Longitude. It covers an area of 22,000 hectares at dam site (37°08’ E and 11°20’ N) that drains into Koga River. The Koga River is a tributary of the Gilgel Abay River in the headwaters of the Blue Nile. The Gilgel Abay flows into Lake Tana. The monthly flow characteristics of the Koga River follow the rainfall pattern. Minimum flow occurs in April. Flow begins to increase in May, in response to the early rains, reaching a peak in August. About 70% of the runoff occurs in the three months from July to September. Its average annual rainfall is 1578 mm. The rainfall has a uni-modal characteristic that extends from May to October.

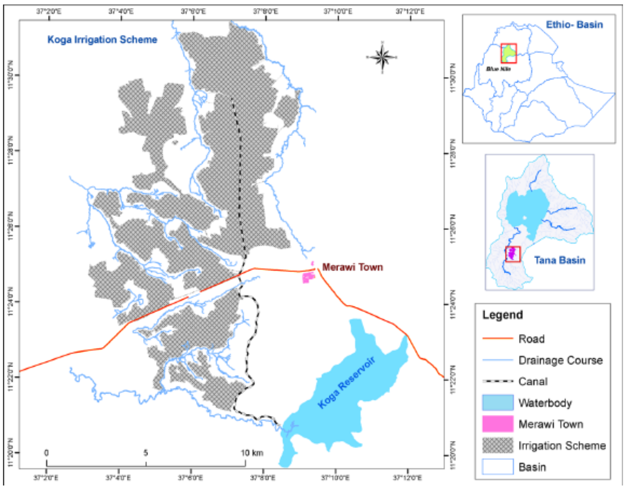

Figure 1: Location map of koga dam and Irrigation Project.

Data collection

Hydrological data were collected from Koga irrigation project office and Ministry of Water and Energy in 2012/13. Crop area, yield, cost of production and farm get prices of crops and reservoir water release, were collected in 2012/13 from office of Koga irrigation project. The soil texture within the command area is uniformly clay and the total available water (TAW) is 160 mm/m [27,28]. The soil moisture content at field capacity, permanent wilting point and the initial available soil moisture in December were 46.71%, 30.93%, and 15.26 mm/m [28].

Model development

Chance constraint linear programming (CCLP) models were developed by incorporating uncertainty of inflows at exceedance probabilities (ρ) of 90%, 80%, 70%, 60% and 50%.

These objective functions were maximization of total yield (Equation 4) in tons and total benefit (Equation 7) in Ethiopian Birr (ETB). Then the decision variables, irrigated land and water for each of five major crops in the project area: maize (*Zea mays L.*), wheat (*Triticum aestivaum*), potato (*Solanum tuberosum L.*), onion (*Allium cepa L.*) and pepper (*Capsicum spps.*) were determined by maximizing the developed model subject to land and water resources availability constraints. Also included in the model was a constraint of limits on the irrigated lands for each crop. This was imposed to allow for diversity and prevent the domination of one crop over the others. Constraint containing variable of stochastic inflow was transformed in to its deterministic programming before optimization [29]. Then the model was solved using Language for Interactive General Optimization (LINGO) version 14. Four scenarios were suggested through this study.

For scenario I and II, the total sum of crop areas were made less or equal to 7000 ha. Irrigated land constraints for each crop was made less or equal to its maximum allowed limit in scenario I (3290, 1260, 1120, 840 and 490 ha for maize, wheat, onion and pepper respectively) but made greater or equal to the maximum limit of each crop except for pepper in scenario II. In scenario III and IV, the sum of total crop areas was less or equal to the potential irrigable area of 7572 ha. Land constraints for each crop was made less or equal to its maximum allowed limits in scenario III (3558.8, 1363,1211.5, 908.64 and 530.04 ha for maize, wheat, onion and pepper respectively) but made greater or equal to the maximum allowed limit of each crop except for pepper in scenario IV.

The following water production function [30] was used to derive objective function.

$$\frac{Ya_c}{Ym_c} = 1 - Ky_{cs}\left(1 - \frac{ETa_{cs}}{ETm_{cs}}\right) \tag{1}$$

where, Ya_c is the actual yield of the crop with the available water (kg/ha), Ym_c is the maximum yield (kg/ha) that could be obtained when there is no limitation of water (Allen et al., 1998). ETa_{cs} and ETm_{cs} are the actual and potential crop seasonal evapotranspiration (mm/season), and Ky_{cs} is the seasonal yield response factor of crop 'c' for the full growing season [30]. Actual and potential crop evapotranspirations were estimated using crop-water simulation model (CROPWAT) version 8.0 for Windows. Seasonal actual evapotranspriration (ETa_{cs}) in mm was estimated as the sum of net irrigation applied and effective rainfall.

$$ETa_{cs} = \sum\nolimits_s \left(\frac{R_{cs}\eta}{A_c} \times 10^5 + Pef_s\right) \tag{2}$$

where, R_{cs} is the irrigation release to crop 'c' in season 's' (Mm^3), η is the irrigation efficiency. A_c is cultivated area under crop 'c'. The adopted canal lining in the irrigation scheme has a conveyance efficiency of 78%, field application efficiency of 62.5% and the overall irrigation efficiency of 48.75% [10]. Pef_s is seasonal effective rainfall (mm) calculated from 80% dependable rainfall of Merawi Meteorological Station using USDA Soil Conservation Service Method in CROPWAT. Seasonal potential evapotranspiration of crop was estimated as

$$ETm_{cs} = \sum_{g=1}^{NG}\left(Kc_g * ETo_g\right) \tag{3}$$

where, Kc_g is crop coefficient of crop 'c' in growth stage 'g' [31] and ETo_g is the reference evapotranspiration in growth stage 'g'. ETo was estimated from long-term monthly averaged values of meteorological data using CROPWAT. Combining equations 1 to 3, seasonal yield maximization objective function (Equation 4) was developed.

$$Ya_{cs} = \sum_{c=1}^{N}\left[A_c\left(Ym_{cs}\left(1 - Ky_{cs} + \frac{Ky * Pef}{ETM_{cs}}\right)\right) + Ym_{cs}\eta * 10^5\left(\frac{Ky_{cs}}{ETM_{cs}}\right)R_{cs}\right] \tag{4}$$

The net benefit for each crop (NB_c) was estimated as:

$$NB_c = P_c Ya_{cs} A_c - C_c A_c \tag{5}$$

where P_c is the market price in Ethiopian Birr (ETB) per ton, Ya_c is the yield per unit area (kg/ha), C_c is the cost of cultivation per unit area (ETB/ha) and A_c is area of crop 'c' in hectare. Total annual net benefit from all command areas of the project was given as:

$$NB_{Tot} = \sum_{c=1}^{N} NB_c \tag{6}$$

Combining Equation 4 to 6, the following objective function for total net benefit was obtained.

$$NB_{Tot} = \sum_{c=1}^{N}\left[A_c\left(P_c Ym_{cs}\left(1 - Ky_{cs} + \frac{Ky * Pef}{ETM_{cs}}\right) - C_c\right) + P_c Ym_{cs}\eta * 10^5\left(\frac{Ky_{cs}}{ETM_{cs}}\right)R_{cs}\right] \tag{7}$$

where, Ya_c and Ym_c are the actual and maximum yields in kg /ha,

The objective functions (Equations 4 and 7) were maximized subject to the following constraints.

$$A_{c1} + A_{c2} + A_{c3} + A_{c4} + A_{c5} \le A_{Tot} \tag{8}$$

$$A_{\min} \le A_c \le A_{\max} \tag{9}$$

$$R_{c1} + R_{c2} + R_{c3} + R_{c4} + R_{c5} \le V_{cs} \tag{10}$$

$$R_{cs\max} = \left(\frac{ETm_{cs} - Pef_s}{\eta * 10^5}\right)A_c \tag{11}$$

$$R_{cs\min} = P_c\left(\frac{ETm_{cs} - Pef_s}{\eta * 10^5}\right)A_c \tag{12}$$

$$S_{t+1} - S_t - P_t + R_t + ER_t + SP_t + EVP_t = I_t^{\rho} \tag{13}$$

$$S_{\min} \le S_t \le S_{\max} \tag{14}$$

$$R_{cs} \ge 0, A_c \ge 0, EVP_s \ge 0, ER_s \ge 0 \tag{15}$$

where, Equation 8 is land resources availability constraint. Total area allocated to each crop cannot exceed total available land (A_{Tot}). A_{c1} to A_{c5} are seasonal area allocated to maize, wheat, potato, onion and pepper, respectively. Equation 9 is maximum and minimum crop area limit imposed during project designing [10]. The cropping pattern used to derive the crop water requirements during irrigation dam designing was 47% maize (3290 ha), 18% wheat (1260 ha), 16% potato (1120 ha), 12% onion (840 ha) and 7% pepper (490 ha) out of 7000 ha area [10]. Equation 10 is water availability constraint. The sums of seasonal water allocated to each crop should not exceed reservoir water supply for irrigation (V_s). R_{c1} to R_{c5} are seasonal water released to maize, wheat, potato, onion and pepper, respectively. Equation 11 is maximum irrigation release to each crop (R_{c5max}). R_{csmax} was restricted by its seasonal potential irrigation requirement ETm_{cs} (Equation 3). Equation 12 is minimum irrigation release to each crop (R_{csmin}) restricted to management allowed depletion (P_c) of the seasonal irrigation requirement. Equation 13 is water balance of reservoir during the monthly time interval 't' in irrigation season estimated by chance constraint form of reservoir storage continuity equation, where, S_{t+1} is storage at the end of time period t, S_t is storage at the beginning of time period t, P_t is 80% dependable rainfall of Merawi station during time period t , R_t is release volume at time period t+1, ER_t is environmental (compensation) release at time period t according to MacDonald [32]. SP_t is the spilled or over flow water. I_t^{ρ} is the expected monthly inflows (I_t) into the reservoir at different ρ values of 90%, 80%, 70%, 60% and 50% which was estimated from the distributions fitted using Cumulative Frequency Program. Transpiration and seepage are seen as a minor contribution to the losses factors [33] and therefore not included in the water balance equation.

EVP_t is the evaporation rate at time period t estimated by Linacre [34] method. Monthly reservoir evaporation (Mm^3) was estimated by multiplying evaporation rate (mm) and reservoir surface area for each month. Reservoir surface area on which evaporation would take place was determined from the best fitted capacity area curve derived using Koga reservoir area, volumes and stage relationships data from MacDonald [35]. The units of all parameters in Equation 13 are in million cubic meters (Mm³). Equation 14 is minimum and maximum storage volumes. S_{min} and S_{max} were minimum and maximum storage limits, respectively. The dead storage volumes of 4.8 Mm³ and full capacity of storage (83.1 Mm³) were used as minimum and maximum storage volume limits, respectively. Equation 15 is non-negativity constraint in which all decision variables were made greater or equal to zero.

Water productivity

Physical water productivity is calculated in terms of yield per volume of irrigation water released (Equation 16), and economic water productivity is calculated in terms of net income per volume of irrigation water released (Equation 17). Finally, the calculated values of water productivities were compared with the actual water productivity values for 2012/13 irrigation season.

$$W_p = \frac{Y}{R_T} \qquad (16)$$

$$W_e = \frac{I}{R_T} \qquad (17)$$

where, W_p is physical water productivity (ETB/m³), Y is total yield (kg) and R_T is total irrigation water released (Mm³), W_e is economic water productivity (ETB/m³) and I is net income (ETB).

Results and Discussion

Irrigation demand reservoir water supply

Gross irrigation (mm) and 100% of irrigation water demands (Mm³) for different scenarios of cropping pattern are presented in Table 1. As it was shown in the table, the maximum water demand occurs in March. According to MacDonald [10], the 7000 ha irrigated area is governed by the 80% reliability yield per annum from the dam. This study has also confirmed that the design reservoir yield could be achieved at all exceedance probability levels of 80% and less when the reservoir is empty at the end of irrigation season (May). Cumulative reservoir inflow was 77.67 Mm³ at ρ 80%.

Equation 18 is the best fit reservoir surface area–capacity curve (R^2=0.99) for Koga irrigation reservoir. Estimated monthly evaporation rate (mm) is shown in Table 2.

$$A_t = -0.002(V_t - 30.4429)^2 + 0.26 * V_t + 2.68 \qquad (18)$$

where, A_t is reservoir area (km²) at month t and V_t is reservoir volume (Mm³) at month t.

Actual irrigation practice

The actual yields, potential yields, production costs and farm gate crop prices in the Koga irrigation scheme for the year 2012/13 are shown in Table 3. It is the farmer who decides the types of crops grown on his farm. As a result, thirteen types of crops were sown in the irrigation project in 2012/13. Out of 7000 ha irrigable lands, a total of 5144.36 hectares were cultivated, 37,920.6 tons of yield was harvested from all crops and net benefit of 113,343,614 ETB was obtained. Sensitivity test showed that the actual values of yield and benefit would not be changed if environmental flow had been permitted for downstream environment. Cultivated areas of major crops: maize, wheat, potato, onion and wheat were 1967, 511, 1318, 83 and 32 ha, respectively. The cultivated areas of these crops except for potato were less than their maximum allowed land limits.

Actual reservoir operation during 2012/13 irrigation season is shown in Table 4. Total seasonal irrigation water released was 67.7 Mm³.

Optimal land and water allocations

The optimal results for irrigated land and water allocated to each crop, the total yield and benefits gained at 80% exceedance probability (ρ) of reservoir inflows under each scenarios are described in the following sections. Under each crop column (Table 5), the first values are land in ha and the values under bracket are allocated water in Mm³.

Scenario I: The global optimal solution under scenario I for total yield and benefit maximizations of 7000 ha of land is shown in Table 5. Both yield and benefit optimization models allocated 97%, 115%, 131%, 132% and 134% of the actual irrigated lands in 2013 irrigation season at ρ 90%, 80%, 70%, 60% and 50%, respectively. The actual yield harvested and the benefit gained during 2012/13 irrigation season was 37,920.6 tons and 113,343,614 ETB, respectively from 5144.36 ha of

Types of Irrig. Demand	Dec	Jan	Feb	Mar	Apr	May	June	Total
Gross Irrigation	235.50	834.80	1453.80	1736.50	1501.9	634.50	64.85	
Scenario I	7.75	15.27	19.00	19.44	13.31	1.31	_	76.08
Scenario II	7.75	16.43	22.14	23.55	16.79	1.81	_	88.47
Scenario III	8.38	17.20	21.54	22.42	15.48	1.42	_	86.44
Scenario IV	8.38	17.77	23.95	25.47	18.16	1.96	_	95.69
Scenario V	7.75	16.43	21.61	23.43	16.97	2.69	0.32	88.88

Table 1: Gross irrigation (mm) and irrigation demand (Mm³) for different scenarios.

Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
123.9	94.2	85.8	87.2	88.2	72.1	63.7	70.5	86.8	125.7	145.6	148.2

Table 2: Monthly reservoir evaporation in mm.

Crop type	Max yield (ton/ha)	Actual yield (ton/ha)	Average production cost (Birr/ha)	Average farm gate price(Birr/ton)
Wheat	6	5.5	8700	4800
Maize	6	2.3	8476	7500
Potato	22	20	12900	3500
Onion	35	16.5	14380	4000
Pepper	2.3	2.2	8730	4000

Table 3: Maximum yield [36] production cost and farm gate price of crops.

Months	Stage (m.a.s.l*)	Volume (Mm^3)	Release (Mm^3)
Oct	2015.10	81.00	1.53
Nov	2014.88	76.00	4.54
Dec	2014.25	66.00	12.82
Jan	2013.25	51.00	15.17
Feb	2012.00	35.00	15.64
Mar	2010.63	21.00	11.94
Apr	2010.00	15.50	5.33
May	2009.50	12.00	0.72
Total			67.7

*m.a.s.l is meters above sea level

Table 4: Actual reservoir operation for the year 2012/13.

Scenario	Maize	Wheat	Potato	Onion	Pepper	Land (ha)	Yield (ton)	% actual yield	Benefit (ETB)	% actual benefit
I	3290 (32.0)	654.3 (7.3)	1120 (13.6)	840 (8.4)	0.0 (0.0)	5904.3	78734.47	108	314072100	177
II	3290 (32.0)	1260 (7.7)	1120 (13.6)	1330 (13.3)	0.0 (0.0)	7000	92161.64	143.	343355800	203
III	3558.8 (34.6)	257.1 (2.9)	1211.5 (14.7)	908.6 (9.1)	0.0 (0.0)	5936.1	82405.86	117	349179700	208
IV	3558.8 (23.8)	1363.0 (8.3)	1211.5 (14.7)	1438.7 (14.4)	0.0 (0.0)	7572	95828.70	153	348946300	208
Actual values						5144.36	37920.6		113,343,614	

Values in the parenthesis are seasonal water (Mm^3) allocated to each crop.

Table 5: Optimal land and water allocation under all scenarios at excedance probability (ρ) of 80%.

ρ value	Released water	Scenario I		Scenario II		Scenario III		Scenario IV	
	(Mm^3)	W_p	W_e	W_p	W_e	W_p	W_e	W_p	W_e
90%	51.3	1.4	5.7	1.6	5.6	1.5	6.1	1.6	5.5
80%	61.3	1.3	5.1	1.5	5.6	1.3	5.7	1.6	5.7
70%	70.3	1.2	4.6	1.4	5.4	1.3	5.2	1.5	5.8
60%	71.3	1.2	4.6	1.4	5.4	1.2	5.2	1.5	5.8
50%	72.2	1.2	4.5	1.4	5.3	1.2	5.1	1.4	5.8
Actual	67.74	0.56	1.67	0.56	1.67	0.56	1.67	0.56	1.67

Table 6: Water productivity under four scenarios.

land. The use of optimization model increased the yield by 93%, 108%, 119%, 119% and 120%, and the benefit by 156%, 177%, 188%, 188% and 189% as compared to the actual yield at ρ 90%, 80%, 70%, 60% and 50%, respectively. No land was allocated to wheat at ρ 90% and pepper at ρ 90% and 80%. The land allocated to wheat at ρ 80% was 51.93 % and it was 100% of their maximum allowed land of 1260 ha at ρ 70%, 60% and 50%. The land allocated to maize was 92.32 % of its maximum allowed land of 3290 ha at ρ 90%, and 100% of its maximum allowed land at ρ 80%, 70%, 60% and 50%. But the land allocated to pepper was 41.69 %, 60.08% and 78.47 % of its maximum allowed land of 490 ha at ρ 70%, 60% and 50%, respectively. The land allocated to potato and onions were 100% of their maximum allowed lands of 1120 and 840 ha, respectively at all ρ values. The slacks or unirrigated lands in scenario I, during both yield and benefit maximizations, were 20130.5, 1095.7, 285.6, 195.6 and 105.5 hectares at ρ 90%, 80%, 70%, 60% and 50%, respectively. These unirrigated lands would make some of the land holders disadvantaged from the irrigation scheme. Under this scenario, 100% of irrigation demand could be met for wheat, potato and onion and 89% for maize. The 11% water deficit for maize is very much less than its management allowed depletion of 55%. Therefore this deficit would not result into significant yield reduction.

Scenario II: The global optimal solutions under scenario II for total yield and benefit maximizations is shown in Table 5. Both yield and benefit optimization models allocated 7000 ha of land for irrigation. The land allocated to all crops except for pepper was 100% of their maximum permitted areas at all ρ values. But no land was allocated to pepper. For example, the optimal amount of areas allocated to maize, wheat, potato and onion at ρ 80% were 3290, 1260, 1120 and 1330 ha, respectively and their corresponding allocated water was 26.7, 7.7, 13.6 and 13.3 Mm^3. In general, the CCLP model improved the yield by 121%, 143%, 159%, 161% and 162%, and the benefit by 153%, 103%, 137%, 139% and 141% of the actual at ρ 90%, 80%, 70%, 60% and 50%, respectively. Under this scenario 100% of irrigation demand could be met for potato and onion, 89% for maize and 63% for wheat ρ 90%. The 37% water deficit for wheat is very much less than its management allowed depletion of 55%. Therefore, the deficit water for maize and wheat would not result into significant yield reductions.

Scenario III: The global optimal solutions for scenario III by relaxing the constraint of total command area up to 7572 ha is shown in Table 5. The total areas that could be irrigated under this scenario using yield and benefit maximization models were 96%, 115%, 131%, 133% and 135% of the 5144.36 ha of actual irrigated area in 2012/13 at ρ 90%, 80%, 70%, 60% and 50% respectively. The CCLP model improved the yield by 102%, 117%, 130%, 132% and 133%, and the benefit by 176, 208

Scenario	Irrigation water released					Irrigated area				
	RHS	Incr-ease	Decr-ease	Min	Max	RHS	Incr-ease	Decr-ease	Min	Max
I	61.3	6.7	7.3	54.0	68.0	7000	Infinity*	1095.7	5904.3	-
II	61.3	5.3	9.0	52.2	66.6	7000	905.4	490	6510.0	7905.4
III	61.3	12.3	2.9	58.4	73.6	7572	Infinity*	1635.9	5936.1	-
IV	61.3	10.8	4.8	56.5	72.1	7572	478.9	530.0	7042.0	8051.0

*Irrigated area coefficient that can be increased indefinitely

Table 7: The right-hand side (RHS) ranges of constraints at ρ 80%.

%, 223%, 224% and 226% of the actual in 2012/13 at ρ 90%, 80%, 70%, 60% and 50%, respectively. The allocated lands of potato and onion at all ρ values were 100% of their maximum allowed lands of 1211.52 and 908.64 ha, respectively. The lands allocated to maize were 2824.3 ha at ρ 90% and 100% of its maximum allowed lands of 3558.84 ha at ρ 80% to 50%. No land was allocated to wheat at ρ 90%. However, 19%, 78%, 85% and 91% of maximum allowed lands of 1362.96 ha of wheat were allocated at ρ 80%, 70%, 60% and 50%, respectively. On the other hand, no land was allocated to pepper at all exceedance probabilities. The slack or unirrigated lands out of 7572 ha of potential irrigable lands were 2627.5, 1635.8, 826.2, 736.2 and 646.2 ha at ρ 90%, 80%, 70%, 60% and 50%, respectively during yield and benefit maximizations. Under this scenario 100% of irrigation demand could be met for wheat, potato and onion, 89% for maize at ρ 80%. Thus, the deficit water for maize would not result into significant yield reduction.

Scenario IV: The global optimal solutions of scenario IV for total yield and benefit maximizations were shown in Table 5. Both yield and benefit optimization CCLP models allocated 100% of the maximum permitted lands to maize, wheat, potato and onion crops but, no land was allocated to pepper at all ρ values. The CCLP model improved the yield by 176%, 208%, 223%, 224% and 226%, and the benefit by 149%, 208%, 258%, 264% and 269% of the actual at ρ 90%, 80%, 70%, 60% and 50%, respectively. Under this scenario 100% of irrigation demand could be met for potato and onion, 61% for maize and 63% for wheat at ρ 80%.Water deficits for maize and wheat would not result into significant yield reduction. Yield and benefit improvements remain almost constant at ρ 70%, 60% and 50% under all scenarios. This is because water supply is greater than irrigation demand at these probabilities of reservoir inflows.

Productivity

Table 6 shows physical water productivity (W_p) and economic water productivity (W_e) under scenario I, II, III, IV and actual conditions at different exceedance probabilities (ρ) of water availability. For ρ 90% to 50%, physical and economic water productivities range from 1.2 to 1.4 kg/m^3 and 4.5 to 5.7 ETB/m^3, respectively under scenario I, 1.4 to 1.6 kg/m^3 and 5.3 to 5.6 ETB/m^3, respectively under scenario II, 1.2 to 1.5 kg/m^3 and 5.1 to 6.1 ETB/m^3, respectively under scenario III, and 1.4 to 1.6 kg/m^3 and 5.5 to 5.8 ETB/m^3, respectively under scenario IV.

The physical and economic water productivities of the actual irrigation practice were 0.56 kg/m^3 and 1.67 ETB, respectively. The W_p and W_e improvements at ρ values of 90% to 50% were 114% to 150% and 169 % to 241%, respectively under scenario I, 150 % to 186% and 217% to 235%, respectively under scenario II, 114% to 168% and 205% to 265%, respectively under scenario III, and 150% to 185% and 229% to 247%, respectively under scenario IV. Optimal cropping pattern improved W_p and W_e by 132 to 205, 168 to 235, 132 to 241 and 186 to 241 under scenario I, II, III and IV, respectively at ρ 80%. Hence minimum and maximum W_p were 132 and 186, respectively and whereas minimum and maximum W_e were 205 and 241 of the actual values, respectively at ρ 80%. Generally, W_p and W_e remained constant from ρ 70% to 50% under all scenarios. Whereas W_p and W_e decreased from ρ 90% to 80% under scenario I and III. Under scenario II, W_p decreased and W_e remained constant. W_p remained constant and W_e decreased at scenario IV from ρ 90% to 80%.

Optimal ranges of water and land allocations

Table 7 shows the right-hand side (RHS) ranges of water and land constraints in which the optimal solutions of yields and benefits are unchanged. For example, at scenario II, the optimal yield of 92161.64 tons and 343355800 ETB could be gained from 7000 ha of land irrigated at ρ 80% using 61.3 Mm^3 of water (Table 5). In this scenario, the reservoir water released for irrigation and the cultivated areas can change between 52.2 to 66.6 Mm^3 and 6510 to 7905.4 ha, respectively (Table 7), but the current optimal values of yield and benefit remain optimal in these intervals or ranges. Among the four scenarios, the minimum amount of land that could be irrigated at ρ 80% was 5904.3 ha at scenario I and the maximum was 8051.0 ha at scenario IV. The optimal irrigated areas under scenario I and III were the minim values of optimal ranges of area allocations for these scenarios. Whereas that of scenario II and IV were within the ranges of optimal area allocations. Therefore, optimal cropping pattern would increase the irrigated area by 15% to 56%, the yield by 108 to 153% and the benefit by 153 to 208% of the actual values at ρ 80%. This implies that the actual irrigated land in 2012/13 was below the optimal values and water released for irrigation was mismanaged.

Conclusion

This study optimizes cropping patterns of five major crops: maize, wheat, potato, onion, and pepper using chance constraint linear programming (CCLP) model under four scenarios of cropping pattern. The yield, benefit, water productivity and irrigated areas under all scenarios were greater than that of the actual values in 2012/13 irrigation season. The study showed that the possibility of irrigating 5904.3 to 8051.0 hectares of land at ρ 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. Optimal water allocations to each crop, under all scenarios of cropping pattern, would not result into significant yield reduction. Thus, it was concluded that the actual irrigated land (5144.36 ha) in 2012/13 was below the optimal values, and water released for irrigation was mismanaged. Therefore, with optimal crop planning and water management, it is possible to irrigate the design command area of 7000 ha. Therefore, the developed CCLP models could be valuable tools for decision making in selecting optimum combination of crops that maximize the benefit/yield of an irrigation project. Knowledge of optimum crop combination is important in determining irrigation demand on which reservoir operation is based. Finally, a study should be made to determine optimal levels of crop water deficit that maximize water productivity and optimization of cropping pattern using computational intelligence techniques.

References

1. Goodarzi E, Ziaei M, Hosseinipour EZ (2014) Introduction to optimization analysis in hydrosystem Engineering. Springer International Publishing, Switzerland.
2. WWAP (United Nations World Water Assessment Programme) (2014) The United Nations World Water Development Report 2014: Water and Energy. Paris, UNESCO.
3. Bruinsma J (2009) The Resource Outlook to 2050: By How Much do Land, Water and Crop Yields Needto Increase by 2050? Prepared for the FAO Expert Meeting on 'How to Feed the World in 2050', 24-26 June 2009, Rome.
4. WWAP (World Water Assessment Programme) (2012) United Nations World Water Development Report 4: Managing water under uncertainty and risk. Paris, UNESCO.
5. Homayounfar M, Lai SH, Zomorodian M, Sepaskhah AR, Ganji A, et al. (2014) Optimal Crop Water Allocation in Case of Drought Occurrence, Imposing Deficit Irrigation with Proportional Cutback Constraint. Water Resources Management 28: 3207-3225.
6. Singh A (2012) Optimalal location of resources for the maximization of net agricultura lreturn. Journal of Irrigation and Drainage Engineering 138: 830-836.
7. Wang LK, Yang CT (2014) Modern Water Resources Engineering. Humana Press, New York.
8. Awulachew SB, Teklu E, Namara RE (2010) Irrigation potential in Ethiopia: Constraints and opportunities for enhancing the system. International Water Management Institute, Ethiopia.
9. MoWR (Ministry of Water Resources) (2002) Water sector development program 2002-2012. Main report volume I. Addis Ababa, Ethiopia.
10. MacDonald (2006b) Koga dam and irrigation project design report. Part 2: Irrigation and drainage. Ministry of water resources, Addis Ababa, Ethiopia.
11. Mujumdar PP (2002) Mathematical tools for irrigation water management- An Overview. Journal of Water International 27: 47-57.
12. Matanga GB, Marino MA (1979) Irrigation planning 1. Cropping pattern. Water Resource Research 15: 672-678.
13. Singh DK, Jaiswal CS, Reddy KS, Singh RM, Bhandarkar DM, et al. (2001) Optimal cropping pattern in a canal command area. Agricultural Water Management 50: 1-8.
14. Regulwar DG, Pradhan VS (2013) Irrigation planning with conjunctive use of surface and ground water using fuzzy resources. Journal of Water Resource and Protection 5: 816-822.
15. Sivanpheng O, Kangrang AM, Lamom A (2009) A Varied-Utilized Soil Type in Linear Programming Model for Irrigation Planning. American Journal of Engineering and Applied Sciences 2: 133-138.
16. Reddy MJ (2006) Swarm intelligence and evolutionary computation for single and multi objective optimization in water resource systems (un published PhD thesis), Department of Civil Engineering, Faculty of Engineering, Indian Institute of Science, Bangalore -560012, India.
17. Felix M, Judith M, Jonathan M, Munashe S (2013) Modeling a small farm livelihood system using linear programming in Bindura, Zimbabwe. Research Journal of Management Sciences 2: 20-23.
18. Rani Y R, Rao T (2012) Multi Objective Crop Planning for Optimal Benefits. International Journal of Engineering Research and Applications 2: 279-287.
19. Sabouni MS, Mardani M (2013) Application of robust Optimization Approach for Agricultural Water Resource Management under Uncertainty. Journal of Irrigation and Drainage Engineering 139: 571-581.
20. Prasad AS, Umamahesh NV, Viswanath GK (2011) Optimal irrigation planning model for an existing storage based irrigation system in India. Irrigation and Drainage Systems 25: 19-38.
21. Mutnuru RA, Ahsan N, Hassan Q (2013) Application of optimization modeling in sustainable agricultural and water resources planning: a case study. International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD) 3: 31-40.
22. Aghajani A, Bidabadi FS, Joolaei R, Keramatzadeh A (2013) Managing cropping patterns agricultural crops of three Counties of Mazandarnprovince of Iran. International Journal of Agriculture and Crop Sciences 5: 596-602.
23. Qureshi AL, Khero ZI, Lashari BK (2012) Optimization of irrigation water management: a case study of secondary canal, Sindh, Pakistan. Sixteenth International Water Technology Conference, IWTC, Istanbul, Turkey.
24. Wankhade MO, Lunge HS (2012) Allocation of agriculturall and to the major crops of Saline Track By linear programming approach: A case study. International Journal of Scientific and Technology Research 1: 21-25.
25. Guo P, Chen X, Tong L, Lib J, Lia M, et al. (2014) An optimization model for a crop deficit irrigation system under uncertainty. Engineering Optimization 46: 1-14.
26. Watkins DW, McKinney DC (1997) Finding robust solutions to water resources problems. Journal of Water Resources Planning and Management 123: 49-58.
27. MacDonald (2008) Koga irrigation scheme manual: operation and maintenance part C. Irrigation and drainage system, Volume 1. Ministry of Water Resources, Addis Ababa, Ethiopia.
28. Abebaw A (2012) Evaluation of stage-wise deficitfurrow irrigation application on maize production at Koga irrigation scheme, West Gojjam (unpublished M.Sc. thesis), Haramaya University, Ethiopia.
29. Mays LW, Tung YK (1992) Hydrosystems Engineering and Management. McGraw-Hill Inc, Singapore.
30. Doorenbos J, Kassam AH (1979) Yield response towater. FAO Irrigation and DrainagePaper 33, Food and Agricultural Organization of United Nations, Rome, Italy.
31. Allen RG, Pereira LS, Raes D, Smith M (1998) Cropevapo transipiration: guidelines for computing water requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy.
32. MacDonald (2006) Koga dam and irrigation project, design report, Part 1: Koga dam. Ministry of Water Resources, Addis Ababa, Ethiopia.
33. Tukimat NNA, Harun S (2014) Optimization of Water Supply Reservoir in the Framework of Climate Variation. International Journal of Software Engineering and Its Applications 8: 361-378.
34. Linacre ET (1993) Data-sparse estimation of lakeevaporation using a simplified Penmanequation. Agricultural and Forest Meteorology 64: 237-256.
35. MacDonald (2004) Kogadam and irrigation project contract KDIP 3: Kogairrigation and drainage system hydrology factual report. Ministry of water resources, Addis Ababa, Ethiopia.
36. FAO (2013) Crop Water Information. Natural Resources and Environment Department: Water Development and Management Unit.

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