Optimal Land And Water Allocation Model For The Maximization of Net Agricultural Return In Drought Prone Regions

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Abstract

In this study, the land and water resources allocation model was developed to determine optimal cropping patterns and water resources allocations at different rainfall probability exceedance levels (PEs) to ensure maximum agricultural return in the Hormat-Golina valley irrigation command area, Ethiopia. To account the uncertainty of rainfall variability, the monthly dependable rainfall was estimated at three levels of reliability (20, 50 and 80% PEs) which are representing wet, normal and dry seasons based on regional experience. The irrigation water demand which was used as an input to the optimization model was estimated at each level of reliability by using CROPWAT model. The net annual returns of optimal cropping patterns were estimated as 181, 179 and 175 million Ethiopia Birr at 20 %, 50 % and 80 % PEs, respectively. The result of the optimal cropping pattern indicates that, the net annual return of the command area was increased to 45.75%, 45.84% and 47.01% than the Government targeted at 20%, 50% and 80% PEs, respectively. The findings reveal that the optimal land and water resources allocation model is very useful to the planners and decision makers to maximize the agricultural return particularly in areas where land and water resources are limited.

1. Introduction

The agriculture productivity has to be increased to fulfill the rising food requirement of the population[1];[2];[3]). This is possible through cultivating more area or effective management of available land and water resources. Increasing cultivation area is difficult due to limitations of the land area being cultivated and it brings environmental disturbance. Particularly, in arid and semi-arid regions, the land and water resources are limited [4]; [5] and food insecurity has become a critical issue especially in developing nations like Africa, Ethiopia. Therefore, both land and water resources should be allocated optimally under a multi-crop situation in a crop growing season for the maximization of net agricultural returns [6]; [7].

In irrigated agriculture, where various crops are competing for a limited quantity of land and water resources, the use of linear programming is one of the best alternative optimization tools for the effective utilization of both resources in sustainable manner [8];[9]. The linear programming is also easy to apply for the optimal allocation of available land and water resources to maximize farm revenue from agricultural fields [10]. Sethi et al. [8] developed linear optimization model for optimal cropping and groundwater management for maximizing the economic return of agricultural products. Crop planning model was developed by Itoh et al. [12] which support decision making of agricultural farms. Vedula et al. [13] presented mathematical model to arrive at an optimal conjunctive use policy for irrigation of multiple crops in a reservoir-canal-aquifer system. The deterministic linear programming and chance-constrained linear programming models were developed by Sethi et al. [13] to allocate available land and water resources optimally on seasonal basis to maximize the net annual return from intensive rice cultivation agricultural fields. Adeyemo & Otieno [13] developed multi objective crop planning model to minimize the total irrigation water and to maximize the total net income in a farmland. A linear programming model was presented by [4] for the optimal land and water resources allocation in order to maximize net annual returns. The model was applied in arid and semi-arid regions where good quality soil and water resources are limited.

A simulation and optimization models was developed by [3] for the optimal planning of cropping pattern, maximization of net benefits and minimization of irrigation water requirements. Singh [9] presented a linear programming model for the optimal land and water resources allocation in order to maximize net annual returns from an irrigated area located in Haryana State of India. The model incorporates reservoir inflow uncertainty but

lacks stream-aquifer interaction and seepage through water conveyance (canals) structures as well as conjunctive use of water resources. Jiang et al. [15] developed process-based regional economic optimization model for maximizing irrigation water use efficiency and economic benefit of an irrigation system. A linear optimization model was developed by [16] to maximize the net annual return from the three old regions of Egypt. Mahmoudzadeh Varzi et al. [17] presented optimization model to maximize farm profit through optimizing water allocation between on-farm production and off-farm leases. The presented model optimizes the water allocation for a single farm and crop using crop water production functions and the concept of deficit irrigation.

Almost in all the previous studies ([13];[3]; [9], the optimization models were applied to maximize agricultural returns without considering hydrological uncertainty and linkage of stream-aquifer for quantifying hydrological responses. The cropping pattern and irrigation water requirement in the command area are governed by the various hydrologic uncertainties such as special and temporal variation of rainfall. Rainfall is an important parameter that drives many hydrological processes and it is one of the main sources of uncertainty in hydrological process responses ([18]; [19]; [20]; ; [21]; [22]). Therefore, management models that are incorporating the uncertainty of a hydrological process are becoming a more reliable tool for irrigation planning and optimal allocation of limited resources. [23]) developed a chance constrained linear programming model to optimize cropping pattern of major crops grown at Koga irrigation scheme, Ethiopia. The model incorporates hydrological uncertainties. An optimal land and water resources allocation model incorporating hydrologic uncertainty was developed by Raul et al., 2011) to determine the optimal cropping pattern for maximizing net annual return. [6] presented an irrigation scheduling model and a linear-programming optimization model under hydrologic uncertainty with a view to manage the available land and water resources of the canal command effectively in canal command of the Hirakud multipurpose major irrigation project of Orissa in eastern India. The recent literature shows growing interest in the use of optimization techniques for optimal allocation of available land and water resources, although they differ significantly in terms of optimization technique, hydrological processes involved, scale of detailing and complexity, and application area ([25]; [26]; [27] [9]; [28]; [29]).

In the present study, a linear optimization model has been formulated for maximizing the net annual return of the crops subjected to various land and water resources constraints. The developed management model incorporates hydrological uncertainty by varying exceedance probability of rainfall, linkage of stream-aquifer for quantifying hydrological responses, and the constraints due to land availability, crop water requirement, irrigation water availability and prevailing farmer's willingness and cropping practices. The present study is first of its kind in the study area and aimed to evolve optimal cropping pattern and water resources allocation policies in the area.

2. Formulation Of Optimal Allocation Optimization Model

In the present study, a linear optimization model has been formulated for maximizing the net annual return of the crops subjected to various land and water resources constraints. The management model has been used to find out the optimal land (cropping pattern) and water resources (groundwater and surface water) allocation policies. Mathematically, the objective function of land and water resources allocation model can be expressed as:

$$\text{Max}Z_p = \sum_{i=1}^2 \sum_{j=1}^n (P_{ij}Y_{ij} - C_{ij})a_{ij} - \sum_{i=1}^2 (C_{sw}(SW)_i + C_{gw}(Gw)_i) \quad (1)$$

Where Z_p is the net total annual income from crops in Birr (Ethiopia currency; US\$ 1=41.2 Birr); i is index for crop season ($i=1$ for rainy season and $i=2$ for non-rainy season); n is the total number of crops grown in a crop season ($n=6$ for $i=1$ and $n=7$ for $i=2$); P_{ij} is market price of the j^{th} crop grown in season i (Birr kg^{-1}); Y_{ij} is yield of the j^{th} crop grown in i^{th} season (kg ha^{-1}); C_{ij} is cost of cultivation per unit area for the j^{th} crop excluding the cost of irrigation water grown with a crop season i (Birr ha^{-1}); a_{ij} is area allocated to crop j grown in season i (ha); C_{sw} is the cost of surface water (birr/ m^3); C_{gw} is the cost of groundwater (Birr/ m^3); $(SW)_i$ is the allocation of surface water in season i (m^3), a decision variable; $(GW)_i$ is the allocation of groundwater in season i (m^3), a decision variable.

The net incomes of crops were calculated from the potential yield of crops, market price of crops and the cost of cultivation. The yield estimates for individual crops are based on the historical performance of the farm, yield potential of the crops, recorded yields of trial and demonstrations, improved cultural practices and efficient management. The current yields of crops were taken from the agronomy feasibility report of Kobo-Girana pressurized irrigation project (Kobo-Girana pressurized irrigation project crop agronomy feasibility unpublished report, 2007). The cost of cultivation of different crops was estimated mainly in consultation of the local farmers and Woreda and Zonal government institutions including agricultural and other pertinent offices. The cost of cultivation includes seed cost, fertilizer, plant protection, draft power and labor costs. The cost of land was not considered in cost of cultivation since it belongs to farmers own land. The administration costs, such as salary of experts, telephone service costs and so on were not considered as it is covered by the Kobo-Girana pressurized irrigation project and Wereda Agricultural Administration Offices. The unit costs of agricultural crops of the local area were taken from Central Statistical Agency of Ethiopia. Since there is no fixed water tariff rate for irrigation paid by the beneficiaries in the study area, the water tariff rate was considered from the other areas having similar water sources. Thus, the costs of canal water were considered as 3 Ethiopian Birr per 1000 m^3 of water which is irrigation canal water tariff of nearby basin (Awash river basin) ([30] and the cost of groundwater were assumed 3.8 Ethiopian Birr per m^3 which is the water tariff of Addis Ababa Town for non-domestic purposes. Summary of cost and net return of dry and wet season crops is shown in Table 1.

Table 1
Summary of cost and net return of Dry and Wet season crops

No	Crop	Grain yield(Birr/ha)	fertilizer (Birr/ha)	Seed rate (Birr/ha)	plant protection (Birr/ha)	Labor cost(Birr/ha)	Draft power (Birr/ha)	Net return (Birr/ha)
Dry season								
1	Maize (dry)	44475	1291	148	240	1260	600	40936
2	Haricot bean	17525	1116	351	90	1980	960	13029
3	Ground nut	59570	744	2072	90	1666	497	54501
4	Onion	204160	2309	111	90	2700	480	198470
5	Tomato	480000	2035	10	70	3300	480	474105
6	Pepper	36340	1882	27	60	3540	480	30351
Wet season								
1	Sorghum	44223	1291	84	240	1380	960	40268
2	Teff	31786	567	319	93	2310	1440	27057
3	Maize (wet)	30836	1291	148	240	1260	600	27297
4	Chickpeas	14720	446	1426	120	1620	1200	9908
5	Mung bean	25024	441	1523	100	1680	1200	20080
6	Sesame	57954	790	406	80	1620	1200	53859
7	Sweet potato	180000	2232	500	60	1860	480	174868

2.1 Model Constraints

Land availability constraints

Land allocated to various crops in different seasons must not exceed the total available land. This limit ratio can be expressed as:

$$\sum_{j=1}^n a_{ij} \leq A_i \forall i(2)$$

Where A_i is the total cultivated command area in season i

Water requirement constraint

The gross irrigation requirement of all the crops grown in the irrigation command area in all the seasons must satisfy the available quantity of groundwater and diverted surface water resources. It can be expressed as:

$$\sum_{j=1}^n a_{ij} * (GIR_{ij}) * 10 \leq (E_{gw}(Gw)_i + E_{sw}(Sw)_i) \forall i(3)$$

Where GIR_{ij} = growth irrigation requirement of crop j grown in season i (mm); a_{ij} = area

allocated to crop j grown in season i (ha); E_{sw} = conveyance efficiency of surface water; E_{gw} = conveyance efficiency of groundwater; $(Sw)_i$ = allocation of surface water in season i (m^3); and $(Gw)_i$ = allocation of groundwater in season i (m^3). In this study, conveyance efficiency of surface water and groundwater were assumed as 98.2 % and 100 %, respectively (Belay, 2012).

The allocation of groundwater and surface water must not exceed their seasonal availability

$$(Gw)_i \leq \sum_{\xi=1}^{43} \sum_{k=1}^6 (Q_{gw})_{\xi,k} * (\Delta t_p)_k * 5.4 * 10^4 \text{ for } i = 1(4)$$

$$(Gw)_i \leq \sum_{\xi=1}^{43} \sum_{k=1}^5 (Q_{gw})_{\xi,k} * (\Delta t_p)_k * 5.4 * 10^4 \text{ for } i = 2(5)$$

$$(Sw)_i \leq \sum_{k=1}^5 (Q_{SD})_{i,k} * (\Delta t_d)_k * 8.64 * 10^4 \text{ for } i = 1(6)$$

$$(Sw)_i \leq \sum_{k=6}^{12} (Q_{SD})_{i,k} * (\Delta t_d)_k * 8.64 * 10^4 \text{ for } i = 2(7)$$

Where $(Q_{gw})_{\xi,k}$ is groundwater pumping from well ξ in the time period k (m^3/s), $(Q_{SD})_{l,k}$ is

diversion from stream reach l in time period k (m^3/s), $(\Delta t_p)_k$ is pumping time in the k^{th} time period (for example, number of days of groundwater pumping in the k^{th} month), $(\Delta t_d)_k$ is diversion time in the k^{th} time period (for example, number of days of stream diversion in the k^{th} month) and i is the number of growing seasons in a year. In the present study area, the crop growing seasons is 2. The first crop growing season (dry season) is from December to May and the second crop growing season (wet season) is from July to November. All the wells assumed to be operated for 15 hours per day and the stream flow diversion for 24 hour per day. The maximum seasonal availability limit of groundwater and surface water resources was obtained from the conjunctive water use simulation-optimization model [31].

Minimum and maximum area constraints

There could be some limitations in the area under a particular crop depending upon the past practices, food requirement, land suitability, water availability and agricultural income. It can be expressed as lower and upper bounds.

$$A_j^l \leq \sum_{i=1}^2 a_{ij} \leq A_j^u \quad j = 1, 2, 3, \dots, 14 \quad (8)$$

Where A_j^l is the minimum area under the j^{th} crop, and A_j^u is the maximum area under the j^{th} crop.

The maximum and minimum areas were set on the consideration of farmer's knowledge on cultural practices of crops and basic food requirements of the local farmers. Based on these criteria, the maximum area was fixed as 50% more than the target area, and the minimum area was set as one quarter of the target area.

3. Model Application

3.1 Description of the Study Area

The study area, Hormat-Golina sub-basin is located in the northern part of Ethiopia, 580 km far away from the capital Addis Ababa, Ethiopia. Geographically situated in $11^{\circ} 59' 00''$ to $12^{\circ} 09' 00''$ north latitude and $39^{\circ} 36' 00''$ to $39^{\circ} 46' 00''$ east longitude (Fig. 1). The total area covers 145 km^2 and it is mostly plain area with flat topography having elevation ranging from 1640 m to 1339 m (a.m.s.l). The valley is bounded by the Alawuha sub-basin from the southern side, the Waja-Golesha Valley to the North, highly rugged mountains of Lasta from western side and extension of Zobul ridge on the eastern side. The outlet of this sub basin is the Golina stream formed through the E-W fracture/fault line running from the Weldia-Lasta Plateau to the Zobul ridge.

The Hormat-Golina valley plain area is characterized as a semi-arid climate. The average annual temperature in the valley plain ranges from 17.5°C to 26°C . In the area, two rainy seasons have been experienced; June to September as main rainy season and March to April as small rainy season. In the remaining months, it is dry. The mean annual rainfall of the watershed is 798.4 mm of which 80% occurs during June to September.

3.2 Irrigation development and cropping pattern

The low lying valley part of the Kobo watershed has been known as the most drought prone region in Ethiopia. As a result, traditional irrigation system has been practiced since long years ago before the commencement of modern irrigation. The irrigation is practiced by diverting the water from the nearby rivers of Alawuha and Golina. However, the modern irrigation has been given emphasis since 1999 in the Kobo valley due to scarcity of rainfall in the area (Co-SAERAR, unpublished report, 1999); and thereby 17000 ha of land is being proposed and start to practice for irrigation mostly from groundwater sources.

Based on this feasibility study, the cropping patterns were proposed on the basis of crop mix and area coverage of individual crops. The crop diversification has been taken as a basic criterion in establishing the crop mix and area coverage. The introduction of various crops into the cropping pattern is assumed to widen the economic base of the project and minimize the risks associated with the growing of a single or limited number of crops. The cropping pattern for the proposed irrigation command area modified from the agronomic report of Kobo-Girana valley pressurized irrigation report is shown in Table 2. The cropping pattern is dominated by annual food crops;

the cereals (sorghum, maize and teff) is assumed to cover the major parts of the area having 110%, followed by pulses (chick pea, haricot bean, mug bean) with 40% and vegetables (onion, tomato, pepper and sweet potato) covers 31% and the remaining proposed area is covered by oil crops (sesame and groundnut).

Table 2
Selected cropping system (wet and dry season cropping)

Crop Type	Wet Season	Dry Season
Cereals	Sorghum, Maize, Tef	Maize
Pulses	Chickpeas, mug bean	Haricot beans
Oil Crops	Sesame	Groundnuts
Root Crops	Sweet Potato	—————
Vegetables	—————	Onion, tomatoes, pepper

3.3 Rainfall data collection and analysis

In this study, the daily rainfall data of 15 years (1996-2010) were collected from National Meteorological Agency, Addis Ababa, Ethiopia observed at Kobo meteorological observatory station which is located within the study area. The daily rainfall data were analyzed to calculate the average monthly and annual rainfall. The bimodal distribution of rainfall seasons have been experienced in the study area. The main rainy season (end of June to September) and the short rain (March to beginning of May) account for about 66% and 12% of the annual total, respectively. The remaining months are generally dry. The highest rainfall occurs during July and August and the dry spell stretches from November to February and another dry spell in June (Fig. 2)

Rainfall plays a key role in appropriate planning and sustainable management of irrigation systems in water-short regions [32]. However, its uneven distribution requires getting knowledge about its special and temporal variability. The distribution of rainfall over the highland areas is modified by orographic effects and is significantly correlated with altitude ([33]; [34]. The study area is plain area with flat topography with an average elevation of 1465 m above mean sea level i.e nearly equals to Kobo Meteorological station elevation (1470 m). The sub-basin area is a relatively small and the spatial distribution of rainfall is strongly correlated with altitude in the region as it is stated by ([34]. The spatial variability and its impacts on the rainfall distribution are almost similar throughout the area. Hence, the rainfall data from this station can represent the rainfall amount in the study area.

Accurate estimation of the temporal distribution of rainfall and its trends are crucial input parameters for securing sustainable management of irrigation system. Since, the total rainfall received in a given period at a location is highly variable and often considered as a major source of uncertainty ([35]; [19]; [36]; [37]; [22]. The analysis of variations of rainfall specially, in arid and semi-arid regions is very crucial where rainfall is scarce and highly variable from one year to another [38]. Hence, in the present study, the 15 years of rainfall data were analyzed for investigation of annual and monthly variations of rainfall in the study area. The frequency analysis of monthly rainfall data has been carried out by using Storm water Management and Design Aid (SMADA) statistical software [39]. This software has a package which is used to carry out frequency analyses designed in different probability distribution functions such as normal, 2-parameter log-normal, 3-parameter log-normal, Pearson type III, log Pearson type III, Gumbel type 1 extremal and generalized extreme value. However, in this study the Normal and Log-normal distributions were considered for carrying out frequency analysis of historical rainfall data set. The

reason for selecting these distributions for frequency analysis is due to the fact that they are commonly used for rainfall data analysis ([40]; [41]. The compatibility of a probability distribution can be assessed through a statistical goodness fit tests as well as graphical display such as probability plots ([42]. In the present study, the better fit probability distribution function was selected by using goodness of fit criteria (coefficient of determination (R^2), and Kolmogorov-Smirnov test). The monthly dependable rainfall values at 20, 50 and 80 % exceedance probabilities (PEs) were used as an input in CROPWAT Model to estimate net irrigation requirement of different crops. Based on regional experience, they are represented as monthly rainfall under wet, normal and dry scenarios, respectively.

3.5 Calculating Crop Water Requirements

In the present study, the computer program available in FAO Irrigation and Drainage Paper No. 56 “CROPWAT” was used for the calculation of crop water requirements of different crops ([43]. First, reference crop evapotranspiration (ET_o) was computed by using FAO- Penman-Monteith (PM) method [43] in CROPWAT 8.0 model. The model requires less intensive data and can easily access databases for climate and crop characteristics. The CROPWAT 8.0 model demands meteorological data, crop data and soil data as an input for irrigation water requirement calculation. The meteorological data such as minimum and maximum temperature, humidity, sunshine and wind speed are used to calculate reference evapotranspiration. For each crop, the crop water requirement (ET_c) was determined using the appropriate crop coefficient (K_c) as:

$$ET_{crop} = K_c * ET_o \quad (16)$$

Where K_c = crop coefficient, ET_o = reference evapotranspiration

The values for crop coefficient (K_c) vary with the crop, its stage of growth, growing season and prevailing water condition. In this study, crop coefficient (K_c) of various crops is obtained from FAO ([44]; [43].). The net irrigation requirements of the crops were calculated by deducting the effective rainfall from the water requirements of the crops. In the present study, the study area under consideration is semi-arid having low rainfall intensity and well-drained soil, and hence USDA-SCS method was selected for the estimation of effective rainfall [45]. For each crop, the net irrigation requirement was determined using the equation:

$$NIR = ET_c - R_e \quad (17)$$

4. Results And Discussion

4.1. Rainfall probability of exceedance (PE)

The frequency analysis of monthly rainfall data of 15 years (1996-2010) was executed using the SMADA statistical analysis software to choose the best probability distribution. The Normal and Log-normal distributions were considered for carrying out frequency analysis of historical rainfall data set using Weibull plotting position. The SMADA statistical software has the capability of computing probability value and plotting the predicted and historical input rainfall against their probabilities. It also draws a best-fit regression straight line through the plotted probability. The predicted rainfall value corresponding to various probabilities and return periods were obtained from the probability plot at each distribution.

The Kolmogorov-Smirnov test and R^2 values of the normal and log-normal distributions in each month were estimated and reported in Table 3. The least Kolmogorov-Smirnov test value and the better R^2 value which is close to one in each month have been selected as best fit distribution. Based on these criteria, the log-normal distribution is selected for the months of January, February, May, June, July, August, September, October, November and December, and for the other remaining months normal distribution is selected as best fit distribution.

Table 3
Kolmogorov-Smirnov test (K-S) and Coefficient of determination (R^2)

Month	Normal		Log-normal	
	K-S test	R^2	K-S test	R^2
January	0.181	0.83	0.116	0.87
February	0.288	0.62	0.151	0.76
March	0.122	0.94	0.186	0.86
April	0.121	0.83	0.162	0.84
May	0.176	0.75	0.103	0.85
June	0.240	0.66	0.164	0.92
July	0.207	0.84	0.143	0.92
August	0.141	0.84	0.133	0.93
September	0.103	0.92	0.092	0.93
October	0.241	0.77	0.127	0.84
November	0.189	0.83	0.085	0.84
December	0.279	0.68	0.165	0.79
* The critical K-S value at 0.05 significance level is 0.338				

Using the best fit probability distribution functions for different months; the probabilities of monthly dependable rainfall at 20, 50 and 80 % exceedance of rainfall were estimated. Based on regional experience, they are represented as monthly rainfall under wet, normal and dry scenarios, respectively. The monthly dependable rainfall at 80, 50 and 20% probability exceedance levels is shown in Fig. 3. The estimated dependable rainfall values with 80 % probability exceedance (PE) are less than the mean rainfall values in both the months, whereas the dependable rainfall values with 20% PEs are more than the mean values in both the months. February is the driest month in the area and the least rainfall is estimated in both the probability exceedance levels. Whereas, August is the wettest month and highest rainfall is estimated in both probability exceedance levels. In February the estimated rainfall values are 9.22 mm, 3.49 mm, and 1.32 mm at 20%, 50%, and 80% probability exceedance level, respectively and in August the estimated rainfall quantities are 297.75 mm, 230.44 mm, 178.38 mm at 20%, 50% and 80% probability exceedance level, respectively.

4.2. Net Irrigation Requirements

The net irrigation requirement of crops at different probability exceedance levels are shown in Table 4. There are two principal cropping seasons, non-rainy (January-May) and rainy (June-September) are prevailing in the study area and crops grown in the command area are categorized into dry season and wet season crops. During rainy season, rainfall is the main source of water for agricultural crops and irrigation water is required additionally to feed agricultural crops as compensation since the area is drought prone area, the rainfall is not sufficient to feed agricultural crops. During dry season irrigation is the main source of water for agricultural crops. Dry season crops are maize, haricot bean, ground nut, onion, tomato and pepper, and wet season crops are sorghum, teff, maize, chickpeas, mung bean, sesame and sweet potato. Maize is grown in both the seasons. The crop water requirement of maize in dry season is more than that in the wet season, because the irrigation water is used as a supplement during wet season in case of rainfall deficiency. Maize requires more water than the other dry season crops at both PE levels. Water requirement of chickpeas is more than the other wet season crops at 20%, 50% and 80% PE levels. The increase in the net irrigation requirement is observed at PE levels of 20 %, 50% and 80% due to decrease in the effective rainfall.

Table 4
Net irrigation requirement (NIR) of different crops in (mm)

I. Dry season crops	PE levels in (%)		
	20	50	80
Maize	551.1	613.3	673
Haricot bean	322.3	381.6	410.1
Groundnut	415.2	489	530.3
Onion	412.5	447.1	468.6
Tomato	406.7	434.4	506.9
Pepper	442.3	468.7	497.4
II. Wet season crops			
Surghum	94.4	177	196.4
Teff	156.3	234.4	235.5
Maize	197.8	203.8	278.7
Chikpeas	238.6	305.7	317.6
Mung bean	93.8	105.5	144.5
Sesame	92.5	182.2	185.2
Sweet potato	209.10	214.30	313.20

4.1 Optimal cropping pattern

A total of six crops (maize, haricot bean, ground nut, onion, tomato and pepper) in dry season and seven crops (sorghum, teff, maize, chickpeas, mung bean, sesame and sweet potato) in wet season were considered in the allocation model to determine the optimal cropping pattern. All these are the proposed crops in the study area in

both the seasons by the agronomists of the Kobo-Girana pressurized irrigation Project Office. The optimization model was run to obtain the optimal cropping pattern of the selected crops at 20%, 50% and 80% exceedence probabilities of rainfall. The model was first run without minimum and maximum area constraints and the optimal land allocation result showed that all the available command area got diverted to tomato during dry season and sweet potato during wet season. One can see that tomatoes achieved the highest increase in its highest net return among other crops and its requirement of irrigation water is not as high as well. The net annual benefit increased by 86% and it indicates that tomato and sweet potato are the most beneficial crops in the command area in their respective seasons as compared to others. However, it could not be encouraged as it affects the overall balance of the agricultural system in the area and due to beneficiary's dietary requirements. Hence, the model was run by setting the minimum and maximum area constraints based on the farmer's knowledge on traditional practices of crops and basic food requirements in the study area.

The optimal cropping pattern of different crops in dry and wet seasons at 20%, 50% and 80% exceedence probabilities of rainfall are presented in Fig. 4. The result derived from the optimization model suggested that there is a large variation than the targeted cropping pattern. The dry season crops such as ground net, onion and tomato have been allotted the maximum area at all PEs. On the other hand, haricot bean and pepper have been allotted the minimum area at all PEs. The area under maize has been limited to 624 ha at all PEs in dry season. The wet season crops such as sorghum, sesame and sweet potato have been allotted to the maximum area possible, whereas chick peas have been allotted to the minimum area at all PEs. Maize has been allotted the maximum area at 20 % and 50 % PEs, and minimum area at 80 % PEs in the wet season. On the other hand, maximum area has been allotted to mung bean at 50 % and 80 % PEs, and minimum area at 20% PEs. The area under teff has been limited to 204 ha, 288 ha, and 321.6 ha at 20 %, 50 % and 80 % PEs, respectively, which is less than the targeted area in both cases.

Based on the results of optimal cropping pattern, the allotted area of crops such as ground net, onion, tomato, sorghum, sesame and sweet potato have increased by 50 % than the targeted area at all PEs. On the other hand, the area under crops such as haricot bean and pepper and chick peas reduced by 33 % than the targeted area at all PEs. The area under the optimal cropping pattern of maize decreases by 17.79 % of the existing area at all PEs during dry seasons. Even though teff covers 35 % of the total targeted area which is more than the other crops except sorghum during wet season because of food subsistence of the beneficiaries, its area under the optimal cropping pattern decreases by 73 %, 62 % and 53 % of the existing area at 20 %, 50 % and 80 % PEs, respectively.

4.2 Optimal water resources allocation

The optimum allocations of canal water and groundwater in the command area in respective seasons at different PEs are shown in Fig. 5 and 6. The optimum canal water allocated to the irrigation command area is 0.63 million m^3 and 0.53 million m^3 during dry season and wet season, respectively at all PEs. It is the maximum available canal water in both the seasons. The optimum allocation of canal water in both the seasons is at its maximum due to minimum canal water cost per cubic meter than the groundwater cost. This amount of water satisfies only 5.89 %, 6.00 % and 6.23 % of the GIR of crops at 80 %, 50 % and 20 % PEs, respectively, during dry season. It also covers 11.87 %, 13 % and 13.83 % of the growth irrigation requirement (GIR) of crops at 80 %, 50 % and 20 % PEs, respectively, during the wet seasons. Generally, it is very less quantity as compared to groundwater use because of limitation of existing canal capacity constraints. The optimum groundwater allocated to the command area is 10.81 million m^3 , 10.41 million m^3 and 10.22 million m^3 at 80 %, 50 % and 20 % PEs, respectively, during dry season. On the other hand, it is 4.47 million m^3 , 4.06 million m^3 and 3.83 million m^3 at 80%, 50 % and 20 % PEs,

respectively, during wet season. In spite of the high cost of pumping as compared to the canal water, the gain in the net annual return is due to the limited canal water availability. As the maximum canal water capacity increases the allocation of groundwater decreases and which is an indication of high cost of pumping that results into the loss of net annual return.

4.3 Net Annual return

The net return obtained per unit area of the allocated crops is calculated by subtracting the production of the crops from the gross profit received. The production cost includes the cost of seeds, chemicals and fertilizers, water harvesting, and labor. The net annual return of optimal cropping patterns for 20 %, 50 % and 80 % PEs are estimated as 181 million, 179 million, 175 million Ethiopian Birr (1 USD=41.2 Birr), respectively. It is evident from the result that there is a gradual decrease from 20 % to 80 % PEs in net annual benefit from the crops due to the gradual increase of GIR irrigation requirements. The comparison of net annual returns associated with the optimal cropping pattern and the government proposed cropping pattern is shown in Fig. 7 at different PEs. The net annual return from the command area increases to 45.75 %, 45.84 % and 47.01 % under the optimal cropping pattern as compared to the government targeted cropping pattern at 20 %, 50 % and 80 % PEs, respectively. The increase in net annual income is primarily due to the optimal allocation of land for various crops.

5. Discussion

The paper presents a linear programming model to determine the optimal crop type area and water volume by source (surface water and groundwater) such that the aggregated net income (revenue minus operational costs including water extraction) of crop production is maximized. The model is formulated and applied in the study area to find out the optimal cropping pattern and optimal allocation of available irrigation water resources in most efficient way for crop production to give the maximum profitability. The optimization model incorporates hydrological uncertainty, linkage of stream-aquifer linkage for quantifying the hydrological responses, and the constraints of the model pertain to the availability of cropland area, water requirements by crop, upper bounds for water extraction volumes by source, lower and upper bounds on cropland area by crop type and prevailing farmer's willingness and cropping practices in the two different irrigation seasons of the year. The developed linear programming model was solved by utilizing MATLAB optimization tool box by writing function code or M-files with the simplex method. For more description on the optimization toolbox, readers may refer [46].

The net return of optimal cropping pattern resulting from the application of the LP model was compared to the existing net return cropping pattern. Different cropping pattern of the area with land restriction was carried out to come up with maximum net profit within available resources and it can be concluded that applying the most beneficial crops like tomato and sweet potato will significantly increase the total net benefit from the agricultural area. This increase in return will help in decision making of farmers what is actually needed to make the available land more profitable. On the other hand, keeping on cultivation of the non-profitable crops with their actual existing areas will reduce the total net benefit and it will limit the allocated areas of the profitable crops and will generally increase the production of the land to satisfy the food requirements. This is important and crucial to support planning for limited land and water resources development and management particularly in the study area and in the country as a whole.

6. Model Assumptions

The following assumptions were considered in developing the model: (1) The objective function and all the constraints are linear; (2) There is no spatial and temporal variation of soil physical and chemical properties; (3) The rainfall is uniformly distributed spatially over the study area (4) Agricultural inputs such as land, labour, remain uniform for any type of agriculture; (5) Each unit of land under any type of agriculture receives the same management practices for a particular crop; (6) Water quality is not considered by assuming that the water quality is not a problem in the specific area for irrigation; (7) A planning horizon of one year with monthly pumping time step was considered for the application of the developed model; and (9) The withdrawal discharge rate from pumping wells and discharge diverted from the canal is kept constant during each planning period, but vary from one planning period to the next.

7. Conclusion

A developed land and water resources allocation optimization model was applied to determine optimal crop pattern and water resources allocation in order to maximize the net agricultural production benefit at different rainfall probability exceedance levels at the Hormat-Golina irrigation command area. To account the uncertainty of rainfall variability, the monthly dependable rainfall at 80%, 50% and 20% probability exceedance was estimated by analyzing the 15 years monthly rainfall data with normal and log-normal distributions. The irrigation crop water requirements of different crops grown in the Hormat-Golina irrigation command area with dependable rainfalls at 80, 50 and 20 % probability exceedance was obtained by using CROPWAT model.

Results obtained for the optimal cropping pattern show that the dry season crops such as ground net, onion and tomato have been allotted the maximum area at all probability levels. On the contrary, haricot bean and pepper have been allotted the minimum area at all probability levels. The wet season crops such as sorghum, sesame and sweet potato have been allotted to the maximum area possible, whereas chick peas have been allotted to the minimum area at all probability levels. Results obtained from the water resources allocation model reveal that the optimum canal water allocated to the irrigation command area is 0.63 million m³ and 0.53 million m³ during dry season and wet season respectively, at all probability levels. Whereas the optimum groundwater allocated to the command area is 10.81 million m³, 10.41 million m³ and 10.22 million m³ at 80 %, 50 % and 20 % PEs, respectively during dry season and it is 4.47 million m³, 4.06 million m³ and 3.83 million m³ at 80%, 50 % and 20 % PEs, respectively, during wet season. The developed optimization model can be used to any irrigation field as a decision support tool to assist planners, farmers and policy makers in determining the most efficient utilization of available land and water resources for the irrigated command areas.

Declarations

Data Availability Statement

Some data used in this study such as climate data, cropping agronomy data, crop coefficient data are available from the corresponding author.

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Ethical Approval

The manuscript is original and has not been submitted elsewhere for the consideration. Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. No data, text, or theories by others are presented.

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by first author (Mulu Sewinet Kerebih). Drafting the work or revising it critically for important intellectual contents was carried out by second author (Proff. Ashok. K. Keshari). All authors read and approved the final manuscript.

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Competing Interests

The authors have no conflicts of interest.

Availability of data and materials

Some or all data that support the findings are available from the corresponding author upon reasonable request.

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Figures

Figure 1

Location map of the study area

Figure 2

Average rainfall (At Kobo Observatory station, 1996-2010)

Figure 3

Monthly dependable rainfall at 80, 50 and 20% probability exceedance

Figure 4

Figure 5
Optimum allocation of surface water and groundwater at different PEs during dry season

Figure 6

Optimum allocation of surface water and groundwater at different PEs during wet season

Figure 7

Comparison of net annual return with optimal cropping pattern and government proposed with different PEs