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Optimizing Water Productivity using Deficit Irrigation, the case of Koga Irrigation project, Ethiopia

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Abstract: Continuous increase of population in Ethiopia, high water demand, occurrence of drought and poor efficiency of irrigation systems lead to real burden on the natural water resources. Finding optimal solution under high demand and limited water supply in the area of farm conditions is complex and requires the use of optimization methods. Thus, optimal irrigation planning and management should be considered for water resource allocation. In this study, linear programming (LP) model was applied for allocation of water for Koga irrigation scheme, Ethiopia using three level of deficit (10%, 20%, 30% ET) irrigation. The objective was to maximize annual net benefit and water productivity considering, water and crop diversification constraints. The model was solved using Microsoft Excel Solver and CROPWAT 8.0 model was used for estimation of crop water requirement at 80 % dependable rainfall. The study indicated that using deficit irrigation, a total of 241.2, 206.9, 179.6 million birr net benefit and 4.0, 3.8, 3.8 birr/m^3 water productivity were achieved using 10%, 20% and 30% deficit irrigation respectively while the actual practice were 229.8 million net benefit and 3.4 birr/m^3. Applying 10% deficit irrigation, the net benefit increases by 5 % while water productivity by 18% as compared to the existing practice. But using 20% and 30% deficit, the net benefit decrease by 10% and 22% respectively while water productivity remain better. Therefore, using 10% deficit irrigation, there could be possibility of irrigating 7349 ha land with better net benefit and water productivity.

Keywords: Water productivity, Deficit irrigation, Linear programming, Koga

Introduction

Water is a diminishing resource and becoming an economically scarce resource not only in arid and semi-arid areas but also in regions where rainfall is abundant (Pereira, 1990). Currently and more in the future, irrigated agriculture will suffer from Irrigation water shortage, particularly in the areas that are characterized by high evaporative demand, low and irregular rainfall, and repeated periods of drought. The great challenge for the coming decades will therefore be the task of increasing food production with less water, particularly in countries with limited water and inefficient water use (FAO, 2002).

Though agriculture is the dominant sector, most of Ethiopia's cultivated land is under rain fed agriculture. Due to lack of water storage and large variation of rainfall in spatial and temporal, there is insufficient water for most farmers to produce more than one crop per season and causes frequent crop production failures due to dry spells and droughts which have resulted in a chronic food shortage problem in Ethiopia (Awulachew *et al.*, 2007). The development of irrigation projects is hoped to ensure food security at household level. Koga dam is a key project for Ethiopian government, as a step towards achieving food self-sufficiency at both national and regional level for a country that has a history of drought and famine (Reynolds, 2012).

The design capacity of Koga irrigation was to irrigate 7000 ha command area (Mott MacDonald, 2006). However, the maximum actual irrigated area was 5343 ha in 2016. This is 76.3 % of the design command areas. In addition, the maximum irrigated command area was 5000 ha in 2014 due to sever water shortage and poor water allocation problems (Abiyu and Alamirew, 2014). Therefore, under such conditions, more efficient water management and resource allocation techniques like deficit irrigation management practices must be adopted. Linear programming model was successfully applied at Koga by Birhanu *et al.*, 2015, to optimized cropping pattern of the initial design (major crops) irrigation using optimal water allocation. The model also successfully applied at Amibara irrigation project in Afar region to maximize net benefit using deficit irrigation (Amare and Olumana, 2012). However, the potential for change in agricultural sector and the volatile nature of market forces, there is scope for further modification of the design system cropping pattern with an introduction of high value crops for farmers to match local and international market.

Material and Methods

Study area description

Koga irrigation project, shown in (Figure 1) is located in upper Blue Nile Basin under Mecha district, south of Amhara Region, Ethiopia where agriculture is the dominant economic activity. The Koga catchment lies between 11°20' to 11°32' North Latitude and 37°02' to 37°11' East Longitude. Mean annual precipitation, average minimum and maximum temperature of the area are 1431 mm, 12 °C, 28 °C respectively. Koga irrigation system is comprised of 12 blocks (command area) and water distribution canals with water flows in gravity system.

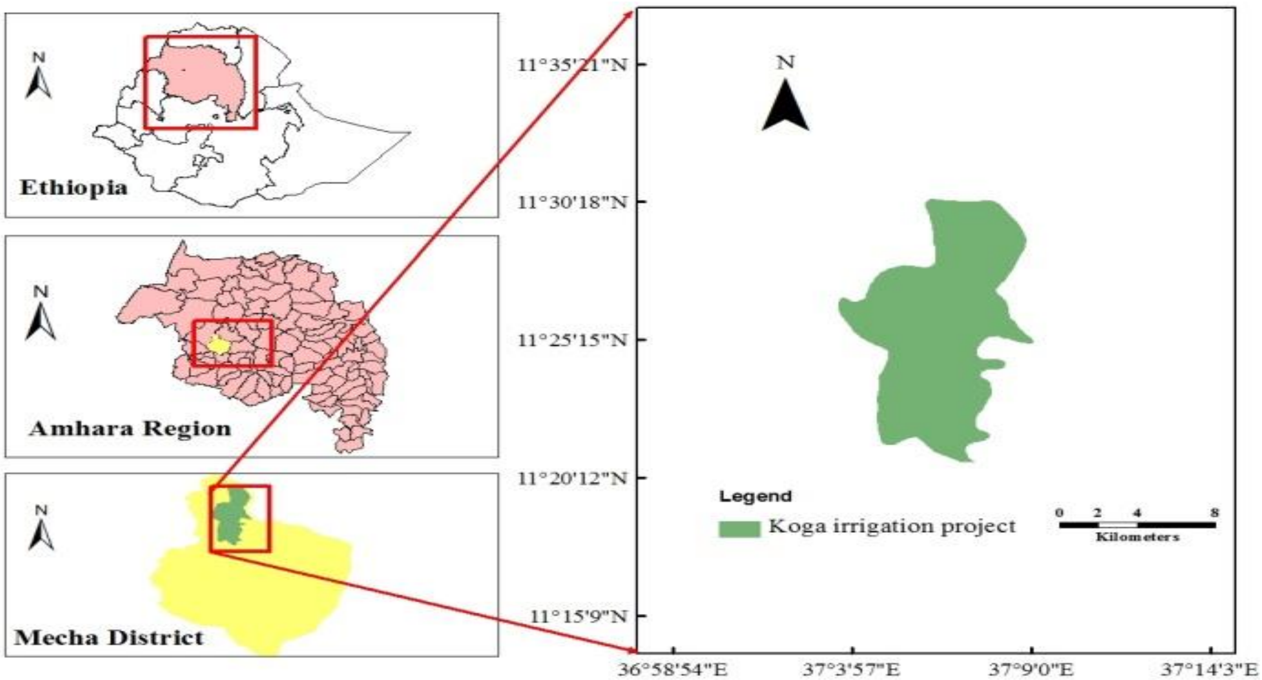

Figure 1 - Location of the study area

Model Formulation

In this study deficit irrigation was optimized using linear programming model. Reference evapotranspiration (ETo) was estimated using (Doorenbos and Pruitt, 1977) FAO penman-Monteith equation (Eqn. 1) and crop and irrigation water requirement was computed using CropWat 8.0 software model window interface.

$$\mathrm{ETo} = \frac{0.408\Delta(Rn - G) + \gamma \dfrac{900}{T + 273} U2(es - ea)}{\Delta + \gamma(1 + 0.34U2} \qquad (1)$$

Where: ETo = reference evapotranspiration [mm day-1], Rn = net radiation at the crop surface [MJ m^{-2} day^{-1}], G = soil heat flux density [MJ m^{-2} day^{-1}], T = mean daily air temperature [°C], U2 = wind speed at 2 m height [m s^{-1}], es = saturation vapour pressure [kPa], ea = actual vapour pressure [kPa], es-ea =

saturation vapour pressure deficit [kPa], Δ = slope vapour pressure curve [kPa $°C^{-1}$], γ = psychrometric constant [kPa $°C^{-1}$]

The study site has only temperature and rainfall data records. Hence temperature and rainfall data were taken from this site while other data were taken from Dangila and Bahir Dar Meteorological stations. Dangila meteorological station has data records from 1997 to 2017 years. Bahir Dar station is also a synoptic station containing all elements of climatic data from 1980 to 2017 record years. Koga scheme is located at 35 km from Bahir Dar and 38 km from Dangila and found in similar agro-ecology. Therefore, the average of the two nearby stations was used for computation of crop water requirement.

Table 1 - Koga irrigation project climate data used

MONTH	TMIN (^oC)	TMAX (^oC)	HUMIDITY (%)	WIND SPEED (KM/DAY)	SUNSHINE (HOUR)	AVERAGE RAINFALL (MM)
January	7.9	27.4	48.1	61	9.5	1.5
February	9.8	29.3	43.3	69	9.7	1.8
March	13.2	29.8	41.5	86	9.2	13.9
April	15.3	30.5	41.8	95	9.1	26.8
May	15.8	29.8	52.5	86	8.5	72.8
June	14.9	27.8	66.5	86	6.9	191.3
July	14.5	25.1	76.3	69	4.6	438.7
August	14.4	24.8	84.5	69	4.6	397.3
September	12.7	25.7	73.2	69	6.3	193.2
October	12.9	26.4	64.3	69	8.7	81.7
November	11.3	26.5	57.2	61	9.4	9.9
December	8.4	26.3	52.3	61	9.7	4.5

Local rainfall data was used for estimation of effective rainfall and it was generated based on 80 percent dependable rainfall, rather than average rainfall (Fig. 2). For this study, USDA Soil Conservation Service; method was used for the estimation of effective rainfall.

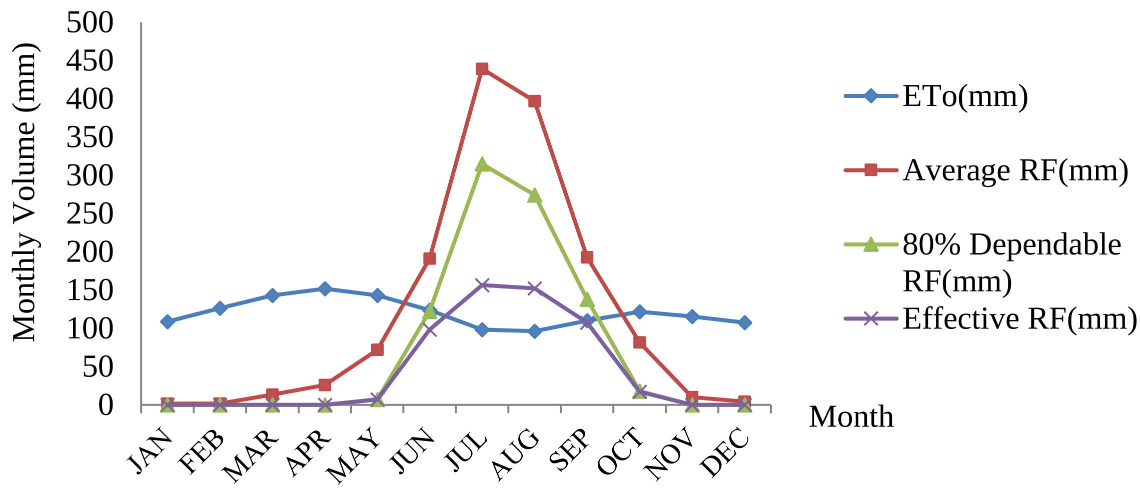

Figure 2 - Koga Effective rainfall, Average rainfall, dependable rainfall and ETo

Dependable rainfall occurs from May to October for six months and the effective rainfall follows the 80 percent dependable rainfall pattern with some deviation throughout the year. The monthly reference evapotranspiration exceeds the monthly rainfall from January to May and from November to December, results a need of compensable irrigation water supply for crop production in the study area during this month.

Three different scenarios were developed for a condition that optimize water productivity and all crops were allowed to experience three different levels of evapotranspiration (ET) depletion occurring continuously over the total length of growing period. A relative evapotranspiration depletion of 10%, 20%, and 30% of CWR was test independently in the model. The yield reductions due to different level of ET deficit were incorporated using the simple linear crop water production function by applying in (Equ. 1). The study was assumed that water is the only constraint variable factor, considering (climate, soil condition, crop variety and crop management practices were remain similar) production that affect yield of crops and yield reduction due to water stress does not affect seed quality and market price of the crop, the effect was only on mass yield of the corresponding crops.

The response of yield to water supply is quantified through the yield response factor (k_y) which relates relative yield decrease (1-Ya/Ym) to relative evapotranspiration deficit (1-ETa/ETm). It is assumed that the relationship between the relative yield (Y_a/Y_m) and the relative evapotranspiration (ET_a/ET_m) is linear and valid for water deficits up to about 50 percent or ($1-ET_a/ET_m = 0.5$) when developing the K_y values of most crops (Doorenbos and Kassam, 1979).

According to Doorenbos and Kassam (1979) crop yield response factor (Ky) on relative yield decrease and relative evapotranspiration deficit is given by the following empirical formula.

$$\left(1-\frac{\mathrm{Ya}}{\mathrm{Ym}}\right)=\mathrm{Ky}\left(1-\frac{\mathrm{ETa}}{\mathrm{ETm}}\right) \tag{2}$$

Where: Ya = actual harvested yield, Ym = maximum harvested yield, Ky = Yield response factor, ETa = actual evapotranspiration, ETm = maximum evapotranspiration

The linear programming model was developed to allocate water that maximizes total benefit and water productivity. While the model constraints were total water availability and maximum area allowed for each crops. Microsoft Office Excel tool of Solver function was used for mathematical model formulation. Irrigated crops and area coverage of the years 2016/17 was collected from Koga irrigation and water management office, Merawi. Similarly important data such that cost of production (fertilizer cost, seed cost, labor and chemical cost), sell prices, yield, planting and harvesting dates of major crops (table 2) was obtained from documented data from koga irrigation and water management office and direct interviews with irrigators. Unit profit was calculated based on the difference of sell price and production cost of irrigated crops. Due to lack of locally validated values, data of crop coefficient (Kc) for estimation of crop water requirement and the yield response factors (K_y) for each growth stage (table 3) was taken from (Allen, 1998) and (Doorenbos and Kassam, 1979) respectively.

Table 2 - Average Production Cost (P_c), Maximum yield (Y_m), Average local price and cultivated area of Existing crops (2016/17)

CROP	WHEAT	MAIZE	POTATO	ONION	PEPPER	BARLEY	TOMATO	GARLIC	CABBAGE
Pc (ETB/ha)	9460	8830	17840	73440	10850	5670	13440	17640	13048
Ym (Kg/ha)	30	58	200	185	55	17	25	100	220
Local price (Birr/ton)	7842	4500	4293	5833	4167	6625	2833	22000	2417
Area (ha)	2003.1	355.4	1053.1	954.0	81.0	131.5	111.3	162.1	491.8

Table 3 - Yield response factor (Ky) and Crop coefficient factor (Kc) values For each crops

GROWTH STAGES		WHEAT	MAIZE	POTATO	ONION	PEPPER	BARLEY	TOMATO	GARLIC	CABBAGE
Initial	Ky	0.20	0.4	0.45	0.45	0.45	0.20	0.40	0.45	0.20
	Kc	0.35	0.4	0.45	0.50	0.35	0.35	0.45	0.70	0.45
Devt	Ky	0.60	1.5	0.80	0.45	0.90	0.60	1.10	0.45	0.20
	Kc	0.75	0.8	0.75	0.75	0.70	0.75	0.75	0.85	0.75
Middle	Ky	0.50	0.5	0.70	0.80	0.70	0.50	0.80	0.80	0.45
	Kc	1.15	1.15	1.15	1.05	1.05	1.15	1.15	1.00	1.05
Late	Ky	0.50	0.2	0.20	0.40	0.20	0.50	0.40	0.30	0.60
	Kc	0.45	0.7	1.85	0.85	0.90	0.45	0.80	0.70	0.90

The objective function

The objective function of the study was maximizing net benefit of the command area. The total profit was estimated using the difference of production cost and final selling price of all cultivated crops at farm gate price.

$$\text{Maximize } Z = \sum_{i=1}^{Nc} PiYiAi - \sum_{i=1}^{Nc} CiAi \qquad (3)$$

Where, Z is the total profit achieved from cultivating the i^{th} crop in Ethiopian Birr (ETB), Pi is the unit sell price of i^{th} crop (ETB qt^{-1}), Ci is production cost of the i^{th} crop (ETB ha^{-1}), Ai is the decision variable, which is the area cultivated for the i^{th} crop, Yi is the yield of the i^{th} crop activity (qt ha^{-1}) and Nc is number of cultivated crops. (1USD Dollar = 23.25 ETB in that irrigation season).

The constraints

The above objective function was subjected to constraints of total seasonal irrigation water supply from the reservoir and crop diversification in the command area.

Land area constraint

The area allocated to each crop during the cropping season should not exceed the total area for cultivation in the command area. The global optimal solution was allowed to relaxing the constraints of total command area up to 7000 ha.

$$\sum_{n=1}^{N} Xn \leq At \qquad (4)$$

Where X_n is crops that are cultivated during the study period and A_t is total relaxing area in the irrigation project.

Water availability constraint

The model was developed using 48.75% of overall project efficiency and the total gross irrigation requirement of all cultivated crops in the command area should not exceed available water for irrigation. Water released from the reservoir during the study period was 70.94 million cubic meter. However, before the commencement of irrigation, 3.74 million cubic meter water was released from the reservoir through irrigation off takes and used for land preparation. Water in November was released from the reservoir through irrigation off takes and used for land preparation. Therefore, in this study 67.47 million cubic meter water was considered as the volume of water released from the reservoir. Mathematically;

$$\sum_{n=1}^{Nc} (CWRi - Peff)Ai \leq Wa * \gamma \qquad (5)$$

Where: A_i is the area covered by i^{th} crop (ha), γ is the project efficiency (%), Wa is the total available water (m^3), CWR_i is the crop water requirement of the i^{th} crop (m^3 ha^{-1}) and Peff is total effective rainfall (m^3 ha^{-1}).

Crop diversification constraint

Since the command area lies in a region where predominantly depends on agricultural economy, the farmers want to ensure production of certain high value crops in addition to the designed cropping pattern. Therefore, constraint of crop diversification was done using the initial design cropping pattern and the newly introduced crops during formulation of the model. In the initial design and planning phase of the project, the crops selected for irrigation in the scheme were wheat (1260) maize (3290), potato (1120), onion (840) and pepper (490) hectares. While barley (132 ha), cabbage (492 ha), tomato (111 ha) and garlic (162 ha) were the newly introduced crop in the scheme and the model was developed based on the maximum area of this crop from the study period and used this area as the maximum allowed area coverage to encourage high value crops in the scheme.

Therefore, the area allocated to each crop should be less than or equal to the maximum allowed land in the cropping pattern and mathematically expressed as;

$$\mathrm{Ac} \leq \mathrm{Amax} \qquad (6)$$

Where A_{max} is Maximum allowed area of crop and Ac is area of crops that to be optimally allocated.

Non-negativity constraints

All decision variables were made greater than or equal to zero (no negative area) is covered by each crop in the scheme.

$$X1 \geq 0, X2 \geq 0, X3 \geq 0, X4 \geq 0, X5 \geq 0, X6 \geq 0, X7 \geq 0, X8 \geq 0, X9 \geq 0 \qquad (7)$$

Where, $X_1 \ldots X_9$ are the decision variables of the land allocated for each crops.

Result and Discussion

The model was generated based on the above constraints to suggest optimal water allocation that gives maximum benefit and water productivity relative to the existing cropping pattern. The yield reduction due to water deficit was estimated based on doorenbos and kassem (1979) equation (2) and the unit profit coming due to yield reduction was estimated accordingly the corresponding crops.

Table 4 - Estimated yield, benefit and IWR under different level of deficit irrigation

CROP	YIELD (qt/ha)			BENEFIT (birr/ha)			IWR (mm/ha)		
	10%	20%	30%	10%	20%	30%	10%	20%	30%
Wheat	27.3	25.0	23.1	10449.1	8790.0	7386.2	4329	3848	3367
Barley	15.5	14.2	13.1	5070.9	4175.8	3418.5	3778	3358	2939
Maize	51.6	46.4	42.2	16947.8	14370.0	12260.9	3818	3394	2969
Potato	180.2	163.9	150.4	75853.7	67405.9	60355.5	4190	3725	3259
Cabbage	200.7	184.7	171.1	57207.5	51603.6	46827.6	5681	5049	4418
Tomato	226.2	206.6	190.1	43121.1	38212.9	34088.5	5106	4538	3971
onion	166.7	151.6	139.1	18226.7	9961.6	3063.8	2910	2586	2263
Garlic	90.1	82.0	75.2	225603.2	203671.5	185367.5	2977	2646	2316
Pepper	49.5	45.1	41.4	13924.8	11691.0	9826.7	3986	3543	3100

Table 5 - Optimal land, water allocation and net benefit using different level of deficit irrigation

Crops	Actual Practice	Deficit Irrigation Scenarios			
		0% (675 MCM)	10% (607 MCM)	20% (540 MCM)	30% (472 MCM)
Wheat	2003	844	844	844	1260
Barley	132	0	0	0	0
Maize	355	3290	3290	3290	3290
Potato	1053	1120	1120	1120	1120
Cabbage	492	492	492	492	492
Tomato	111	111	111	111	111
Onion	954	840	840	840	221
Garlic	162	162	162	162	162
Pepper	81	490	490	490	490
Total Area (ha)	5343	7349	7349	7349	7146
Net Benefit ($1x10^6$ ETB)	229.8	283.1	241.2	206.9	179.6
Water Productivity (ETB/m^3)	3.4	4.2	4.0	3.8	3.8
Benefit change (%)	0	+23	+5	-10	-22

From Table (3), three level of deficit irrigation were investigated and the model reallocated the actual cropping pattern to the optimal land that maximized total benefit and water productivity. Using optimal water, there could possibility of increasing land from 5343 to 7349 ha, net benefit from 229.8 to 283.1 million birr and water productivity from 3.4 to 4.2 birr/m^3. The model allocated 844 ha of land for wheat and the rest crops were reach their maximum allowed limit of land except barley, not compute the allocated area. This implies that the actual irrigated land in 2016/17 irrigation season was below the optimal values and the water released for irrigation was mismanaged. Figure 2 shows net benefit changes under different level of deficit irrigation using optimal cropping pattern.

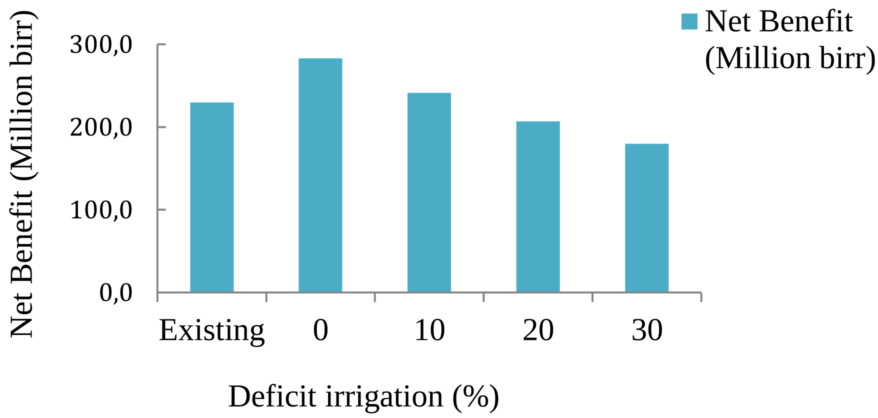

Figure 3 - Net benefit change using deficit irrigation scenario

The sub-optimal water allocation of the model showed that a total 241.2, 206.9, 179.6 million birr net benefit and 4.0, 3.8, 3.8 birr/m^3 water productivity were achieved using 10%, 20% and 30% deficit irrigation respectively. This implies that 10% deficit irrigation increases the net benefit by 5 % and water productivity by 18% as compared to the existing irrigation practice in the scheme but using 20% and 30% deficit the net benefit could decrease by 10% and 22% respectively. On the other hand, water productivity was better as compared to actual irrigation practice, implies that water management in the scheme was poorly controlled.

The land allocated to maize, potato, onion, pepper, cabbage, tomato and garlic were attained 100% of their maximum allowed land while wheat attained (844 ha) land which is 67% of the maximum allowed land (1260 ha) in the design document. But no land was allocated to barely which is out of the maximum allowed land (132 ha). This result reveals that barley was not a competent crop in the cropping pattern system due to low productivity in the scheme.

Conclusion

Hence, the purpose of this study was to optimize water productivity of Koga irrigation system by changing the designed cropping pattern to optimal cropping pattern that maximizes net benefit using linear programming model under water deficit.

The study showed that possibility of irrigating 7349 ha of land with deficit irrigation when supplies are limited via drought and other factors at probability of 80% dependable rainfall by optimizing cropping pattern using irrigation efficiency of 48%. From the result, irrigators could choose high value crops, optimal area and irrigation level for selected crops that maximize net benefits. Knowing the relationship between water and yield reduction due to water stress is important to decide amount of water applied and yield production. Optimization and effective use of water is one of management alternatives that improve water productivity under uncertainty situations. Reducing the amount of used water to the land under deficit irrigation conditions, the irrigated area and net benefit becomes decreased the amount of saved water is maximized.

Under deficit irrigation, Increasing area coverage of the newly introduced (high value) crops, except barley could increase net benefit and water productivity however if not allowed, benefit maximization was below the optimal water allocation scenario in the scheme.

The overall result indicated that optimal cropping pattern considering maximum net benefit could be attained using 10% deficit irrigation. The applicability of the model can increase when many of the actual situations and constraints of the system are incorporated.

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