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Optimizing Reservoir Operation Policy Using Chance Constraint Nonlinear Programming for Koga Irrigation Dam, Ethiopia

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Abstract One of typical problems in water resources system modeling is derivation of optimal operating policy for reservoir to ensure water is used more efficiently. This paper introduces optimization analysis to determine monthly reservoir operating policies for five scenarios of predetermined cropping patterns for Koga irrigation scheme, Ethiopia. The objective function of the model was set to minimize the sum of squared deviation (SSD) from the desired targeted supply. Reservoir operation under different water availability and thresholds of irrigation demands has been analyzed by running a chance constraint nonlinear programming model based on uncertain inflow data. The model was optimized using Microsoft Excel Solver. The lowest SSD and vulnerability, and the highest volumetric reliability were gained at irrigation deficit thresholds of 20 % under scenario I, 30 % under scenario II, III and V, and at 40 % under scenario IV when compensation release is permitted for downstream environment. These thresholds of deficits could be reduced by 10 % for all scenarios if compensation release is not permitted. In conclusion the reservoir water is not sufficient enough to meet 100 % irrigation demand for design command areas of 7,000 ha. The developed model could be used for real time reservoir operation decision making for similar reservoir irrigation systems. In this specific case study system, attempt should be made to evaluate the technical performance of the scheme and introduce a regulated deficit irrigation application.

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1 Introduction

Management of reservoir systems from planning to operation is very challenging for water resources planners and managers since the problem deals with many complicated variables such as reservoir inflows, volume of storages, water demands as well as considerable risk and uncertainty. The stochastic nature of reservoir inflows adds greatly to the complexity of the problem (Taghi et al. 2009). In cases where real time operating policies are required, the decision makers face greater challenge in handling updated reservoir inflow forecasts (Fayaed et al. 2013). Therefore, derivation of simple and flexible optimal operating policy for reservoir to ensure water is used more efficiently is one of the classical problems in water resources systems modeling.

Real-time operation of river–reservoir systems requires specific operating rules. These rules are guides for water conservation and release policies prepared for reservoir operators. Several types of rules range from very simple and static to dynamic for considering the varying states of inflow and physical characteristics of a reservoir in each time period. One of the simplest rules for reservoir operation is the rule curve, which specifies the target storage at the end of each month (Karamouz et al. 2003).

However, rule curves are static forms of operating policies that do not get any feedback from reservoir storages and current hydrologic situations such as predicted inflows to reservoirs in the following months (Karamouz et al. 2003). Hence, rule curves are not very efficient policies, particularly when water inflows and demands are highly varied, but they have been widely used because of their simplicity. Moreover, rule curves prescribe reservoir releases based on limited criteria such as current storage levels, season and demands (Khare and Gajbhiye 2013). In general, rule curves, do not allow a fine-tuning (and hence optimization) of the operations in response to changes in the prevailing conditions (Husain 2012). Application of deterministic and stochastic optimization models for reservoir operation has led investigators to define non-static types of operating rules/policies (Jothiprakash and Shanthi 2006; Karamouze 2003; Singh 2012).

The operating policy is a set of rules for determining the quantities of water to be stored or released from a reservoir or system of several reservoirs under various conditions (Wurbs 2005). In reservoir operating policies, the decision variable (i.e., release) depends on variables representing the state of the system for each month, including: inflow to the reservoir, water demand, storage at the beginning of a month and inflow forecast for the next month (Karamouz et al. 2003; Vedula and Mujumadar 2005).

Therefore, the operation policies in optimization models are like the contents of a table in which various combinations of characteristic values for a state variable and the optimal release are presented in each row (Karamouz et al. 2003). To define reservoir operating policies, several optimization models were used in the past. Linear programming (LP) model was used to evaluate the optimal performance of the Eleviyan Dam based on reservoir inflows (Sattari et al. 2013).

Nondominated Sorting Genetic Algorithm (NSGA-II) model showed a better improvement in the reservoir operation system and mitigated possible water crisis sufficiently due to climate change rather than LP model (Nadrah et al. 2014). A hybrid model that optimizes the conventional rule curve coupled with hedging rules has good performance in extracting the optimum policy for reservoir operation under both normal and drought conditions in comparison to applying the rule curve alone (Taghian et al. 2014).

A chance-constrained LP model was used for short term reservoir operation (Duranyildiz et al. 1999). Monthly storage yield functions were developed using Stochastic Dynamic

Programming Model (Ananda and Shrivastava 2013). The efficiency of the Eleviyan irrigation dam system was investigated by LP model that maximized the water release for irrigation purposes after municipal water need were met (Taghi et al. 2009). Stochastic dynamic programming (SDP) model was used to obtain optimal operating policy (Baliarsingh 2010). Dynamic programming model for real-time reservoir operation was developed by Hajilal et al. (1998). Genetic Algorithm and Excel Optimization Solver were used for optimal short term cascade reservoir operation (Asfaw and Saiedi 2011).

Although many successful applications of optimization techniques to reservoir operation studies have been reported in the literature, no universally proven technique exists (Husain 2012). Nandalal and Bogardi (2013) also added that there is no general algorithm for all reservoirs, and is to be tackled independently for developing the optimal operating strategies. Hence, reservoir operation still remains an active research field (Husain 2012). Dynamic programming also becomes computationally bounded on problems of moderate size and complexity. Linear programming cannot be applied when either the objective function or the constraints become non-linear. Due to complex relationships among different physical and hydrological variables or because of specific objectives being served by system, nonlinearity exists in various reservoir systems operation problems (Rani and Moreira 2010).

Moreover, as future inflows or storage volumes are also uncertain, the challenge is to determine the best reservoir release or discharge for a variety of possible inflows and storage conditions (Loucks and van BeeK 2005). 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 (Watkins and McKinney 1997).

Because of non linearity of the reservoir systems and the uncertainty of inflows, a chance constraint non linear programming (CCNLP) model which uses the statistical behavior and distribution of the river inflows was applied in this reservoir operation study. The use of Microsoft Excel Solver rather than sophisticated computer programs would be easily applied to manage the varying water supply and demand conditions. This study illustrates the application of the CCNLP model to Koga irrigation reservoir in Ethiopia.

This reservoir has been operated using non-optimized fixed guiding curves relating reservoir water level and volume versus irrigable area (MacDonald 2008), and operator's subjective judgment. In the past irrigation years, reservoir water has been used to irrigate less than 73.5 % of design command areas which implies that either the reservoir water was mismanaged or insufficient to irrigate all command areas.

Moreover, as cropping pattern varies year to year in the Koga irrigation scheme due to farmers' preferences, socioeconomic factors and government directives, the amount of reservoir releases would vary as well. Under these circumstances, development of dynamic optimal reservoir operation policy is mandatory for efficient water utilization. Therefore, the objective of this study is to develop monthly optimal reservoir operation policy using a chance constraint non linear programming model. This would enable decision makers or reservoir operators to stipulate the desired monthly reservoir releases as a function of varying water supply and demand conditions.

2 Material and Methods

2.1 Description of the Study Area

The Koga Irrigation dam is located at 37°08' E and 11°20' N, South of Lake Tana in the Blue Nile River Basin, Ethiopia (Fig. 1). The Koga catchment lies between 11°10' and 11°22' North Latitude and 37°02' and 37°17' East Longitude. Its catchment covers an area of 22,000

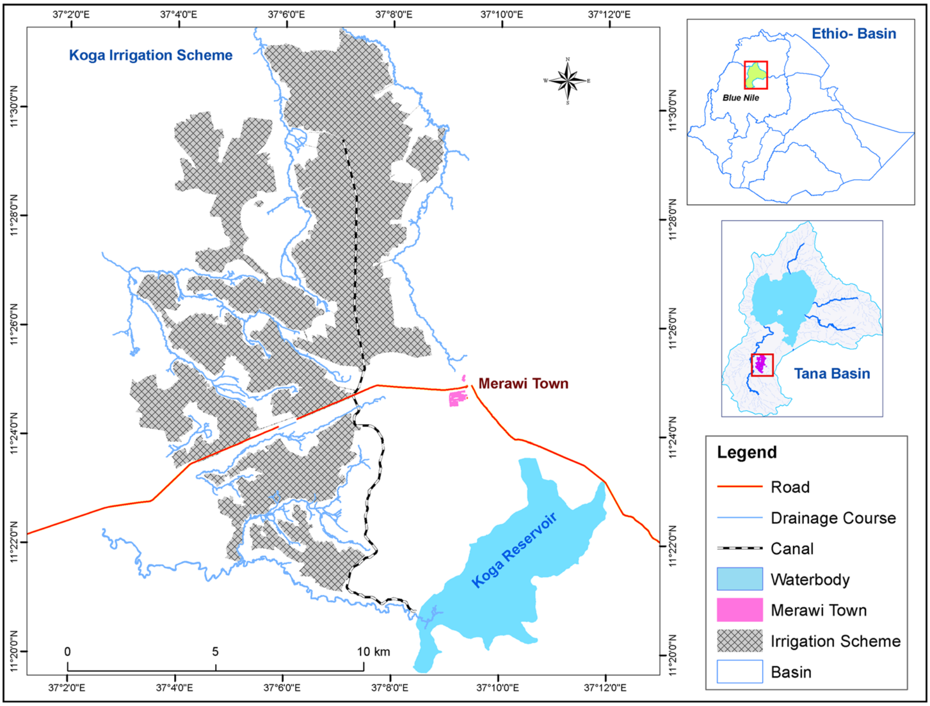

Fig 1 Koga Irrigation and Watershed Management Project (adapted from Ernst 2012)

hectares at dam site (MacDonald 2004). Koga irrigation system is comprised of a water supply source (reservoir) behind a semi homogeneous earth fill dam, a water distribution canals and demand centers (12 command areas covered by the irrigation network). The general characteristics of the dam and irrigation scheme are summarized in Table 1.

2.2 Irrigation and environmental demand

Reservoir operation model requires estimates for reservoir inflows, irrigation and environmental water demands, evaporation and conveyance losses. Expected monthly inflows into the reservoir at 90 %, 80 %, 70 %, 60 % and 50 % probability of exceedance (ρ) were estimated

Table 1 Characteristics of Koga dam and irrigation scheme

Scheme characteristics	Magnitude/Quantity
Catchment area	22,000 ha
Dam height	21 m
Dam crest length	1,730 m
Reservoir area	1,750 m
Reservoir capacity	83.1 M m^3
Irrigation area	7,000 ha
Beneficiary family head	1,400
Main canal discharge	9.1 m^3/s
Spillway discharge	335.4 m^3/s

Source: (MacDonald 2004)

from the distributions fitted using Cumulative Frequency Program. Irrigation demand was estimated using CROPWAT 8:0 for five scenarios (I, II, III, IV and V) of specified cropping patterns for maize, wheat, potato, onion and pepper crops (Table 2). Scenarios I to IV were determined using a chance constraint linear programming model. Scenario V is the irrigation project's design cropping pattern (MacDonald 2006). Monthly compensation releases for downstream environment are shown in Table 3.

2.3 Model Development

The objective of reservoir operation is to minimize the annual water supply deficit function (Eq.1). This function is defined as the sum of the squares of the differences between the quantity of water released from storage and the target requirement for all intervals (months) of the irrigation season. Fig. **2** shows sequential allocation of reservoir water in monthly interval with in irrigation season. Monthly target irrigation requirements were obtained from monthly gross irrigation water calculated for specified cropping patterns. The irrigation system efficiency of 48 % (MacDonald 2006) for the conveyance and application losses was used.

Reservoir storage was determined by available storage at the beginning of every month and the expected inflows during the month. The inflow to the reservoir was treated as a stochastic state variable in the reservoir continuity equation for solving the CCNLP problem. In chance-constrained models for reservoir operation, deterministic constraints involving hydrologic parameters subjected to uncertainty are replaced by probabilistic statements (Mays and Tung 1992).

The developed CCNLP model was solved using Excel Optimization Solver (EOS) integrated with Microsoft Excel. The information needed by EOS are target cell, changing cell and constraints and the adjustment of maximum run-time, iterations, precisions, tolerance, convergence, and defining linear or non linearity of the problem. Quadratic extrapolation which can improve results on highly nonlinear problems was used to obtain initial estimates of the basic variables in each on- dimensional search.

The deficit function to be minimized (Z_t) is given by:

$$Minimize, Z_t = \sum_{t=1}^{T} (R_t - D_t)^2 \tag{1}$$

Subject to:

(i) Reservoir storage continuity equation

Water balance of reservoir during irrigation season t is governed by chance constraint reservoir storage continuity equation.

$$S_{t+1} - S_t - P_t + R_t + ER_t + EVP_t = I_t^{\rho} \tag{2}$$

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 rainfall during time period t, R_t is release volume at time period t+1, ER_t is

Table 2 Cropping pattern scenarios in hectares

Scenarios	Maize	Wheat	Potato	Onion	Pepper	Total area
Scenario I	3290	654	1120	840	0	5904
Scenario II	3290	1260	1120	1330	0	7000
Scenario III	3559	1067	1212	909	0	6746
Scenario IV	3559	1363	1212	1439	0	7572
Scenario IV (design)	3290	1260	1120	840	490	7000

Table 3 Monthly compensation release (Mm^3)

Months	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Flows	1.56	0.80	1.07	0.97	0.80	0.65	0.80	6.65

Source: (MacDonald 2006)

environmental (compensation) release at time period t, EVP_t is evaporation rate at time period t (Eq.9), ρ represents the exceedance probability levels of 90 %, 80 %, 70 %, 60 % and 50 % of reservoir inflow volume and I_t^ρ is inflow volume during time period t. All variables are expressed in million cubic meters (Mm^3).

(ii) Storage boundary constraint

The reservoir storage in any month should not be more than the capacity of the reservoir, and should not be less than the dead storage capacity and is represented by

$$S_{\min} \le S_t \le S_{\max} \tag{3}$$

where, $S_{\max}$ is the storage capacity of the reservoir (83.1 Mm^3) and $S_{\min}$ is the dead storage volume (4.80 Mm^3).

(iii) Surface area constraint:

$$A_{\min} \le S_t \le A_{\max} \tag{4}$$

where, $A_{\min}$ and $A_{\max}$ are minimum and maximum surface area constraints, corresponding to minimum and maximum storage volume limits, respectively. The values of minimum and maxim surface areas are 2.69 Mm^2 and 19.12 Mm^2.

(iv) Release constraint

Amount of water to be released (R_t) from the reservoir for irrigation purposes should meet the irrigation demands of pre-defined cropping pattern.

$$R_t \le D_t \tag{5}$$

where, D_t is the target demand for irrigation (Mm^3).

(v) Over flow constraint

When the final storage in any month exceeds the capacity of the reservoir, the constraint is given by:

$$Of_t = S_{t+1} - S_{\max} \tag{6}$$

where, Of_t is surplus from the reservoir during the month 't'.

(vi) Canal capacity constraint

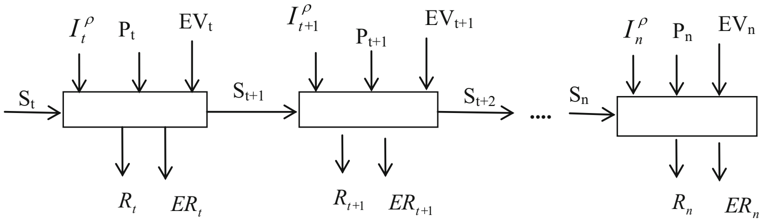

Fig. 2 Sequential monthly allocation processes

Monthly reservoir release should not be greater than maximum canal capacity.

$$R_t \leq CC_t \tag{7}$$

where, $CC_t$is canal capacity for time interval 't'. The main canal was designed to convey 1.2 L/s/ha to 7583 ha of total potential irrigable area (McMahon et al. 2006). The upstream main canal design discharge is 9.1 m^3/s. Therefore, CC_t of 24.37 Mm^3 per month was used.

(i) Non-negativity

All the decision variables must be greater than or equal to zero.

$$R_c \geq 0, A_c \geq 0, EVP_t \geq 0, ER_t, Of_t \geq 0 \tag{8}$$

Monthly precipitation data for the Merawi meteorological station was used to estimate monthly rainfall volume on the reservoir surface area. Reservoir surface area for each month t was estimated substituting the reservoir volume in to area -capacity curve fitted using data shown in Table 4. The evaporation loss (EVP_t) is a nonlinear function of the reservoir surface area (A_t) at period t.

$$EVP_t = e_t * A_t \tag{9}$$

where e_t is evaporation rate (mm/day) estimated using a Simplified Penman Equation (Linacre 1993). Monthly reservoir volume available for irrigation from June to November (wet season) was calculated by subtracting evaporation losses, and adding inflows and rainfall on the reservoir surface using Microsoft Excel Solver. No compensation release was deducted in this case as it is not permitted in wet season. Finally, the reservoir volume at the end of November was used as initial storage while optimizing the release.

2.4 Reservoir Performance

The purpose of performance measures is to have a mechanism to quantitatively compare, for alternative operating plans, the effectiveness of the reservoir system in meeting specified objectives. Consequently, the performance measures must be a function of the storage and release parameters which define an operating policy. In this study, reliability and vulnerability, and sum of square deficit (SSD) of reservoir release for meeting demand were used as reservoir system performance indices.

Reliability is the probability of success. The success interval is an interval in which the amount of water meeting demand is more than a specific threshold. The threshold can be 100 % or less of demand. Reliability estimates can be computed on either a period or volumetric basis. Period reliability can be defined as the proportion of time that the reservoir is able to meet demands. Volumetric reliability (R_v) is the ratio of the volume of water supplied to the volume demanded (McMahon et al. 2006) (Eq. 10).

$$R_v = \frac{V_S}{V_d} \tag{10}$$

Table 4 Koga reservoir area, volumes and stage relationship

Contour (m)	2004	2006	2008	2010	2012	2014	2016
Area (km^2)	0.19	0.98	2.92	7.14	11.84	15.83	19.99
Volume (Mm^3)	0.20	1.00	4.80	14.20	33.80	61.50	97.60

Source: (MacDonald 2006)

Table 5 Gross irrigation (mm) and irrigation demand (Mm^3) for different scenarios

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

where, V_s is the volume of water supplied and V_d is the volume of water demanded during a given period. Vulnerability measures the possible magnitude of a failure if one occurs. Maximum vulnerability (Eq.11) is a suitable indicator of reservoir performance (Kjeldsen and Rosbjerg 2004).

$$\nu_{\max} = \max\{\nu_j\} \tag{11}$$

where, ν_j is maximum irrigation water deficit among all the continuous failure or unsatisfactory months and $\nu_{\max}$ is maximum vulnerability. In this study, six thresholds of 100 %, 90 %, 80 %, 70 %, 60 %, 50 % of the irrigation demand which are equivalent to 0 %, 10 %, 20 %, 30 %, 40 % and 50 % deficit irrigation, respectively were used to compute volumetric reliability and vulnerability for exceedance probability of 80 % reservoir inflows. Then the best scenario was selected based on minimum sum of square deviation (SSD), the highest reliability and minimum vulnerability indices. Finally, optimal monthly reservoir operation policies (storage and release values) in the form of table were presented and their rule curves were developed.

3 Results and Discussion

3.1 Irrigation Demand

Gross irrigation (mm) and 100 % of irrigation water demands (Mm^3) for different scenarios of cropping pattern are presented in Table 5. As it was shown in the table the maximum water demand occurs in March.

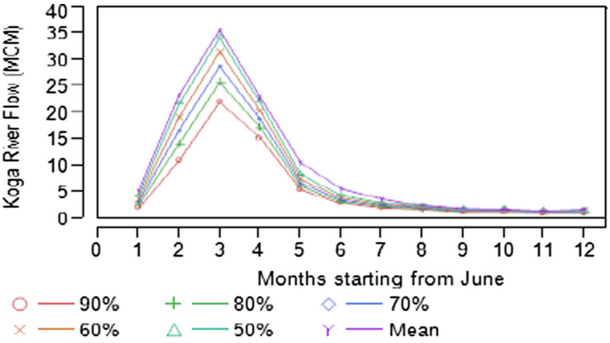

Fig. 3 Koga river flow at different probability levels

Table 6 Cumulative reservoir inflows (Mm^3) when it is empty at May

ρ	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
90 %	1.90	12.80	34.×80	50.00	55.45	58.26	60.20	61.85	63.05	64.27	65.24	66.21
80 %	2.52	16.61	42.37	59.53	65.62	68.79	70.99	72.84	74.15	75.49	76.57	77.67
70 %	3.08	19.76	48.54	67.28	73.99	77.51	79.94	81.95	83.36	84.79	85.95	87.16
60 %	3.66	22.79	54.32	74.66	82.06	85.96	88.65	90.80	92.32	93.83	95.07	96.39
50 %	4.30	25.94	60.11	81.99	90.22	94.57	97.55	99.85	101.48	103.07	104.39	105.84

3.2 Reservoir Water Supply

Expected monthly inflow into the reservoir at 90 %, 80 % and 70 %, 60 % and 50 % probability of exceedance (ρ) is shown in Fig. 3. The higher probability levels indicate low flows and the lower ones indicate high flows. The volume of reservoir inflow begins to increase in June and reaches its maximum in August. Then rapidly decreases to November following the decline of rainfall. It is only base flow that flows into the reservoir from December to May (dry season).

Cumulative reservoir inflows and reservoir storage is shown in Table 6. According to MacDonald (2006), the 7000 ha irrigated area is governed by the 80 % reliability yield per annum from the dam. This 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) (Table 6). Cumulative reservoir inflow was 77.67 Mm^3 at 80 % probability of exceedance (ρ). The reservoir storage at the end of November with carry over year storage of 4.8 Mm^3 was 78.58 Mm^3 at ρ 80 %. This volume was used as initial storage during optimizing reservoir operation.

Eq.12 is the best fitted reservoir surface area –capacity curve for Koga irrigation reservoir.

$$A = 2.68 + 0.26 * V - 0.002(V - 30.4429)^2 \tag{12}$$

where, A_t is reservoir area (km^2) at month t and V_t is reservoir volume (Mm^3) at month t. Estimated monthly evaporation rate (mm) is shown in Table 7.

3.3 Actual Reservoir Operation

The actual data of reservoir stage, volume and irrigation releases recorded for the year 2012/13 is shown in Table 8. No compensation release was permitted to downstream environment but used for irrigation purpose. Before the commencement of irrigation season (i.e., December), a total of 1.54 Mm^3 of the reservoir water was released through irrigation off take and utilized for land preparation. From this amount, 0.52 Mm^3 was released in October and 1.02 Mm^3 in November. While optimizing reservoir operation policy, water stored at the end of November and the reservoir inflows from December to May at ρ 80 % have been considered. For this reason, the water released before December was not considered during comparison of the optimized irrigation releases with the actual releases in 2012/13. Hence, the total water utilized for irrigation purpose from December to May would be 66.2 Mm^3.

Table 7 Monthly reservoir evaporation (mm)

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 8 Actual reservoir operation for the year 2012/13

Months	Stage (masl*)	Volume (Mm^3)	Release (Mm^3)
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

* masl=meters above sea level

3.4 Optimal Reservoir Operating Policies

Based on minimum sum of square deficit (SSD) criterion, the best reservoir operation policies selected under all scenarios at exceedance probability (ρ) of 80 % with and without compensation release permitted are shown in Table 9 and Table 10, respectively. From the results of the reservoir operation analysis (Table 9), sum of squared deficit (SSD) was minimized to near zero under all scenarios at maximum allowable deficit of 20 % for scenario I, at 30 % for scenario II, III and V, and at 40 % deficit for scenario IV. In this case, reservoir operation with the lowest thresholds of water deficit and SSD is scenario I. Having minimum SSD would reduce the risk and consequences of irrigation water supply shortages in the irrigation project. Therefore, reservoir operation is the most reliable and the least vulnerable at scenario I and the least reliable and the most vulnerable at scenario IV at ρ 80 %.

If compensation release is not permitted, SSD would be near zero at 10 % irrigation deficit for scenario I, at 20 % irrigation deficit for scenario II, III and V, and at 30 % irrigation deficit for scenario IV at ρ 80 % (Table 10). Based on minimum thresholds of deficit irrigation and SSD, scenario I was the most reliable, scenario II, III and V were the second most and scenario IV was the least reliable reservoir operations.

Table 9 Reservoir operation policies for different irrigation thresholds and scenarios with compensation release at ρ 80 % of reservoir inflow

Variables	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total release	SSD	% Deficit
Release (I)		6.19	12.21	15.19	15.55	10.64	1.04	-	60.82	1.00	20 %
Storage (I)	73.60	67.41	54.25	37.68	20.72	9.23	7.88	-			
Release (II)		5.42	11.49	15.50	16.47	11.75	1.26	-	61.89	1.00	30 %
Storage (II)	73.60	68.18	55.72	38.82	20.89	8.28	6.77	-			
Release (III)		6.5.86	12.04	15.08	15.68	10.82	0.98	-	60.47	1.00	30 %
Storage (III)	73.60	67.74	54.74	38.28	21.15	9.46	8.16	-			
Release (IV)		5.43	12.00	16.31	17.36	12.22	0.85	-	64.19	0.00	40 %
Storage (IV)	73.67	68.17	55.20	37.49	18.72	5.74	4.80	-			
Design release (V)		5.42	11.50	15.13	16.40	11.87	1.87	0.21	62.37	1.00	30 %
Design storage (V)	73.60	68.19	55.73	39.20	21.34	5.89	6.45	6.10			
Actual release	4.54	12.82	15.17	15.64	11.94	5.33	0.72	-	66.17		
Actual volume	76.00	66.00	51.00	35.00	21.00	15.50	12.00	-			

Table 10 Reservoir operation policies for different irrigation thresholds and scenarios without compensation release at ρ 80 % of inflow

Variables	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Total release	SSD	% deficit
Release (I)		6.97	13.74	17.10	17.49	11.97	1.17	-	68.44	1.00	10 %
Storage (I)	75.10	68.13	54.23	36.82	18.91	6.98	6.29	-			
Release (II)		6.07	13.01	17.58	18.70	13.29	1.30	-	69.95	1.10	20 %
Storage (II)	75.10	69.03	55.84	37.92	18.77	5.53	4.80	-			
Release (III)		6.70	13.76	17.23	17.93	12.37	1.13	-	69.11	1.10	20 %
Storage (III)	75.10	68.40	54.48	36.94	18.59	6.28	5.68	-			
Release (IV)		5.86	12.43	16.76	17.82	12.71	1.37	-	66.95	1.00	30 %
Storage (IV)	75.10	69.24	56.62	39.50	21.17	8.39	7.42	-			
Design Release (V)		6.00	12.94	17.08	18.54	13.35	1.92	0.25	70.08	1.20	20 %
Design Storage (V)	75.10	69.10	55.97	38.55	19.53	6.19	4.80	5.29			
Actual release	4.54	12.82	15.17	15.64	11.94	5.33	0.72	-	66.17		
Actual volume	76.00	66.00	51.00	35.00	21.00	15.50	12.00	-			

3.5 Performance Measures

The performance measures of a CCNLP models at exceedance probability of 80 % under different irrigation deficit levels with and without compensation release permitted are shown in Table 11 and Table 12, respectively. From Table 11, the values of the lowest sum of square deviations (SSD) were near zero, vulnerability reliabilities were one, and the maximum volumetric reliabilities were near zero at irrigation deficit thresholds of 20 % under scenario I, 30 % under scenario II, III and V, and 40 % under scenario IV when compensation release is permitted for downstream environment.

Similarly, these performance indices were gained at irrigation deficit thresholds of 10 % under scenario I, 20 % under scenario II, III and V, and 30 % under scenario IV when compensation release is not permitted for downstream environment. SSD of zero indicates that irrigation water demand has been met at all monthly time intervals in irrigation season. Similarly, vulnerability of zero shows the maximum irrigation water deficit among all the continuous failure or unsatisfactory periods is zero. Volumetric reliability of one implies that 100 % of the irrigation demand has been met throughout irrigation season. The results of these performance measures denote that irrigation demand has been met throughout irrigation season at the stated thresholds of deficit irrigation under all scenarios.

Table 11 Performance tests of reservoir operation at ρ 80 % with compensation release

Deficit	Scenario I			Scenario II			Scenario III			Scenario IV			Design		
	SSD	R_v	ν	SSD	R_v	ν	SSD	R_v	ν	SSD	R_v	ν	SSD	R_v	ν
0 %	23.8	0.85	2.22	104.00	0.73	4.84	87.90	0.75	4.45	179.3	0.67	6.37	105.4	0.72	4.75
10 %	3.70	0.94	0.76	41.20	0.81	2.96	31.80	0.83	2.61	85.00	0.75	4.34	42.6	0.80	2.89
20 %	1.00	1.00	0.01	8.00	0.91	1.22	4.70	0.93	0.89	26.30	0.84	2.31	9.20	0.90	1.31
30 %	0.00	1.00	0.00	1.00	1.00	0.01	1.00	1.00	0.01	2.30	0.96	0.52	1.00	1.00	0.01
40 %	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00
50 %	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00

Table 12 Performance tests of reservoir operation at ρ 80 % without compensation release

	Scenario I			Scenario II			Scenario III			Scenario IV			Design		
Deficit	SSD	R_v	ν	SSD	R_v	ν	SSD	R_v	ν	SSD	R_v	ν	SSD	R_v	ν
0 %	6.70	0.92	1.11	62.1	0.79	3.73	49.50	0.81	3.35	121.8	0.73	5.26	61.9	0.79	5.63
10 %	1.00	1.00	0.01	16.7	0.88	1.85	11.10	0.90	1.50	47.10	0.81	3.23	17.6	0.88	1.80
20 %	0.00	1.00	0.00	1.10	0.99	0.15	1.00	1.00	0.01	8.10	0.91	1.20	1.20	0.98	0.23
30 %	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	1.00	1.00	0.01	0.00	1.00	0.00
40 %	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00
50 %	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00

Reservoir operation of scenario V was the best among scenario II and III for the following reasons. First, scenario V has best combinations of all crops with the lowest onion crop (which is perishable) area allocation. Hence, scenario V has the least risks of vegetable crop damage. Second, the area cultivated under scenario V is greater than that of scenario III but equal with that of scenario II. Hence, as large area cultivated, greater land holders benefitted and greater job opportunities could be created for daily laborers.

3.6 Optimal Operating Rule Curves

Optimal operating rule curves derived from the best reservoir operation policies from Table 11 and Table 12 are shown in Fig. 4 and Fig. 5, respectively. The curves indicate the desired storage volumes of the reservoir and release at any particular month. These curves stipulate how water is to be stored and released during the subsequent months based on the current state of the storage volume and time of the irrigation season at 80 % probability of exceedance. The results dictate that the patterns of the optimal rule curves for storage versus time are similar to the actual rule curve. But the actual curve lies above the optimal curves in April and May. This implies that more water was left at the end of irrigation season. This reduces the reservoir efficiency. However, the patterns of optimal release rule curves are not exactly similar with that of the actual. This was mainly due to the time lag of irrigation commencement in addition to the use of static rule curves by dam gate operator.

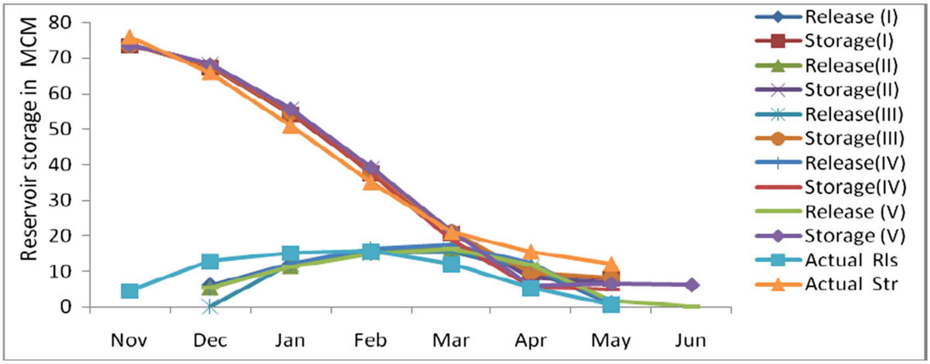

Fig. 4 Operating rule curves for irrigation with compensation release

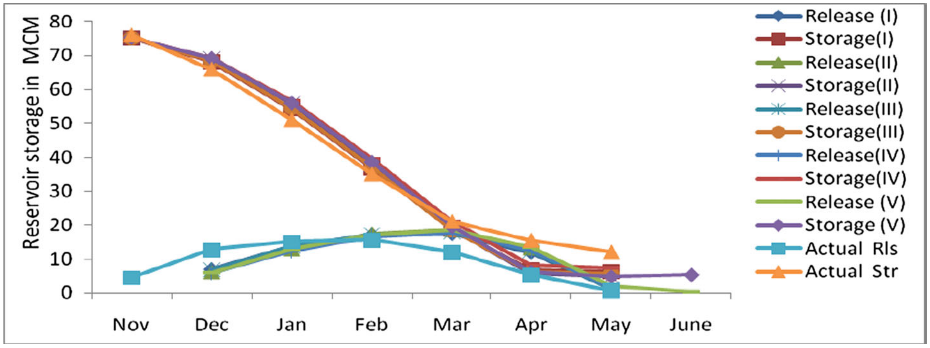

Fig. 5 Operating rule curves for irrigation without compensation release

4 Conclusions

In this study, a chance constraint non linear programming optimization was applied to determine monthly operating policies (storage and releases) for five scenarios of predetermined cropping patterns for Koga irrigation scheme, Ethiopia. The objective function of the model was set to minimize the sum of squared deviation (SSD) from the desired targeted supply at exceedance probability (ρ) of 80 %.

The results of the reservoir operation analysis showed that the most reliable and the least vulnerable reservoir operation was obtained at scenario I. Scenario II, III and V were the second most reliable and scenario IV was the least reliable and most vulnerable scenario. However, reservoir operation of scenario V would be the best amongst scenario II and III for best combinations of all crops having the least risks of crop damage, and larger numbers of land holders benefitted from greater area cultivated and the subsequent higher job opportunity for laborers. The total design command area of 7,000 ha, denoted by scenario V, could be irrigated at maximum thresholds of 30 % irrigation deficit with higher reliability and without significant vulnerability to water shortages. Its thresholds of deficit could be reduced to 20 % if compensation release is not permitted for downstream environment. This threshold of deficit could be reduced by far if the irrigation efficiency is improved from the current 48 %.

If all of compensation release is used for irrigation, the thresholds of deficits for all scenarios would be reduced by 10 % from that of irrigation with compensation release permitted. The study also demonstrated that the simplicity and flexibility of Microsoft Excel Solver in efficiently optimizing the operation policy of an existing reservoir for varying water supply and demand conditions. The developed model could be used by operators or decision makers, given simple training, for real time reservoir operation decision making system. Finally, it was recommended to study the application efficiency of furrow irrigation and conveyance efficiency of irrigation canals, determination of optimal thresholds of deficit irrigation for major crops grown in the project area to maximize water productivity, and optimal cut off time for furrow irrigation using real-time infiltration prediction techniques.

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