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Planning for irrigation using reservoir yield and crop planning models

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Abstract
Planning an irrigation project involves knowledge of the reservoir yield. Reservoir yield is the amount of water that can be supplied from a reservoir over a period of time. Estimation of the annual reservoir yield that can be expected from the reservoir is vital for planning an irrigation project. Among the many methods, yield model is a relatively simpler and quicker method for estimating reservoir yield. It is a general purpose, implicitly stochastic linear-programming screening model that greatly reduces the size of the constraint equations needed to describe reservoir system operation and provide a reasonable estimate of the annual reservoir yield for a desired reliability. This study attempts to estimate the optimal annual yield, using reservoir yield model, that could be obtained from the proposed Morand reservoir project in the middle zone of Narmada Basin in the State of Madhya Pradesh, India, and work out optimal allocations of land and water resources, using crop planning model, to develop cropping patterns for the annual reservoir yields that can be obtained from the reservoir for different degrees of annual project dependability. The linear programming method is used for both the models. The yield model provides a reasonably acceptable estimate of annual reservoir yield for planning a reservoir project.

INTRODUCTION

Determination of reservoir yield is an essential requirement for the planning of a reservoir project. Especially in the cases where the reservoir capacity is fixed by conditions and circumstances at the site, it is necessary to estimate how much water the reservoir with a given capacity will yield over a period of time at a specified reliability. Reservoir yield is dependent upon inflow and will vary from year to year. The safe, or firm, yield is the maximum quantity of water that can be guaranteed during a critical dry period, which is taken in practice as the period of lowest natural flow on record. Several methods are available for the determination of reservoir yield. Among the many methods, yield model is a relatively simpler and quicker method for estimating reservoir yield. It does not require operating policy, which is difficult to have for a project yet at a planning stage. It has been demonstrated that in several cases the yield model provides a reasonable estimate of the reservoir yield (Stedinger et al., 1983).

In this study an attempt is made to estimate the optimal annual yield that could be obtained from the proposed Morand Reservoir project using yield model. Morand Reservoir is a major irrigation project proposed in the middle zone of Narmada basin in the State of

Madhya Pradesh, India. It is located at 63 km from the confluence of a tributary on the left bank of the Narmada River. The reservoir is planned for an active storage capacity of 258 million cubic metre (m cu m). The culturable command area envisaged to bring under irrigation with the project is 36,544 hectare (ha).

YIELD Model

Yield model [Loucks et al., 1981] is a general purpose, implicitly stochastic linear-programming screening model. It is an approximation to the full optimisation model incorporating some approximations to reduce the size of the constraint set needed to describe reservoir system operation when long time periods are considered, but has the ability of using a long period of data without becoming computationally intractable. For a hydrologic record of n years, each having T periods, the number of constraints in yield model is reduced from $2nT$ to $2(n+T)$ and the number of variables from $2nT+T+2$ to $2(n+T)+3$.

The assumptions made in the yield model include:

The within-year flows of the critical period are assumed to be some appropriate fraction (β_t) of the total annual yield Y. The value of β_t is selected to be the ratio of the inflow in period t of the driest year to the total inflow of that year.

The annual evaporation volume loss in each year y is based on the estimated average storage volume from which the area of water spread is determined. The storage-area relationship is approximated to a linear relation which otherwise is non-linear.

The model consists of a set of constraints on storage volumes, capacities, and inflows similar to those used in the full optimisation model (with an annual instead of a monthly time step) and an additional set of within-year or monthly constraints based on a critical period year (Loucks et al., 1981). The simple yield model with an objective of maximising the annual reservoir yield Y for a given active storage capacity K_a is presented as follows:

Maximise Y (1)

Subject to:

1. Over-year storage continuity, for each year:

$$S_y = S_{y-1} + I_y - \alpha_y Y - E_y - R_y \quad \forall y \quad (2)$$

2. Over-year storage volume capacity, for each year:

$$S_y \leq K_0 \quad \forall y \quad (3)$$

3. Within-year storage continuity, for each within-year period t:

$$s_t = s_{t-1} + \beta_t(Y + \Sigma e_t) - y_t - e_t \quad \forall t \quad (4)$$

4. Sum of within-year yields to over-year yield:

$$\Sigma y_t = Y \quad \forall t \quad (5)$$

5. Crop water requirement fraction:

$$y_t = \mu_t Y \quad \forall t \quad (6)$$

6. Definition of estimated evaporation losses, for each year:

$E_y = E_0 + [S_y + \Sigma(½ (s_{t-1} + s_t)\gamma_t]E \qquad \forall\ y,t$
(7)

7. Monthly evaporation loss:

$$e_t = \gamma_t E_0 + ½ (s_{t-1} + s_t)\gamma_t E \qquad \forall\ t \qquad (8)$$

8. Total active reservoir capacity, for each period t:

$$K_0 + s_t \le K_a \qquad \forall\ t \qquad (9)$$

Where,

Y = annual reservoir yield,
y_t = within-year reservoir yield, which is a fraction of Y, in period t,
S_{y-1} = initial over-year storage volume in year y,
S_y = final over-year storage volume in year y,
I_y = annual inflow in year y,
R_y = excess release in year y,
s_{t-1} = initial within-year storage volume in critical period t,
s_t = final within-year storage volume in critical period t,
E_0 = average annual fixed evaporation loss,
E_y = annual evaporation volume loss for year y,
e_t = evaporation loss in period t,
E = average annual evaporation loss rate per unit active storage volume,
β_t = ratio of inflow in period t to the total inflow of the critical year,
α_y = fraction of annual yield available in year y,
γ_t = fraction of the annual evaporation loss in period t,
μ_t = fraction of irrigation water requirement for period t,
K_0 = over-year capacity, and
K_a = total active storage capacity.

Determination of the distribution of annual reservoir yield over the periods, t, in a year makes it necessary to include unit irrigation water requirement fraction in the constraint equation (μ_t in equation 6) for some assumed cropping pattern. It has been observed that when crop water requirement fraction is not incorporated in the model, yield distribution behaves as though there were no storage facility following only the availability of inflow.

ANALYSIS OF THE RESULTS

In this study annual reservoir yield is determined for an active storage capacity of 258 m cu m. A twenty-two year net inflow data is used for the analysis. Three separate cases of annual project dependability are studied in the determination of the annual reservoir yield:

Case 1 - 100% annual project dependability with uniform annual yield from reservoir for all years,

Case 2 - 75% annual project dependability with 80% of annual yield to be made available from reservoir during failure years,

Case 3 - 75% annual project dependability with variable annual yield during failure years.
For the monthly distribution of the annual reservoir yield, fraction of water requirement for the crops in the cropping pattern proposed by the Tribunal (The Narmada Water Disputes Tribunal, 1978) are considered.

The annual reservoir yield during a failure year in Case 3 is taken to be varying depending on the magnitude of inflow available in that year as is the case in simulation and deterministic LP models. For this, since there was no provision in the yield model (Loucks et al., 1981), α_y in equation 2 is taken as the ratio of the inflow in a failure year to the lowest inflow amongst the successful years. This case provides comparison with other models.

The results of yield model are given in Table 1. From the results observed, it appears that Case 3 gives the highest annual yield compared to Cases 1 and 2. These two Cases guarantee annual reservoir yield with some degree of dependability during critical flow years, while Case 3 maintains 75% annual project dependability without guaranteeing a specific amount of annual reservoir yield during failure years. This, as observed, resulted in reduced overall annual reservoir yield for Cases 1 and 2.

Table 1. Annual Reservoir Yield from Yield Model for Different Cases.

Month	Reservoir Yield (m cu m)			
	Variable	Case 1	Case 2	Case 3
Jul	y_1	2.401474	2.821596	4.150203
Aug	y_2	2.401475	2.821597	4.150204
Sept	y_3	14.04547	16.50262	24.27323
Oct	y_4	12.02317	14.12654	20.77832
Nov	y_5	14.02967	16.48406	24.24592
Dec	y_6	12.82893	15.07326	22.17082
Jan	y_7	16.05196	18.86014	27.74083
Feb	y_8	13.23971	15.5559	22.88072
Mar	y_9	15.2304	17.89486	26.32102
Apr	y_{10}	15.2778	17.95055	26.40294
May	y_{11}	17.2369	20.25238	29.78863
Jun	y_{12}	14.44044	16.9667	24.95582
Annual	Y	149.2074	175.3102	257.8586

PERFORMANCE OF YIELD MODEL RESULTS

Results of the yield model were tested for their performance with simulation. The performance result shows less number of deficit years than the model allows in the Cases considered. Cases 1 and 2 show no deficit in any year when tested by simulation. Case 3 shows three deficit years, less by two years than the expected five. The simulation results for Cases 2 and 3 show respectively 100% and 86% annual project dependability against 75% in the yield model.

Hence, the annual reservoir yield estimates of the yield model in this study can be judged reasonably acceptable considering the higher degree of project dependability that is observed from the simulation tests.

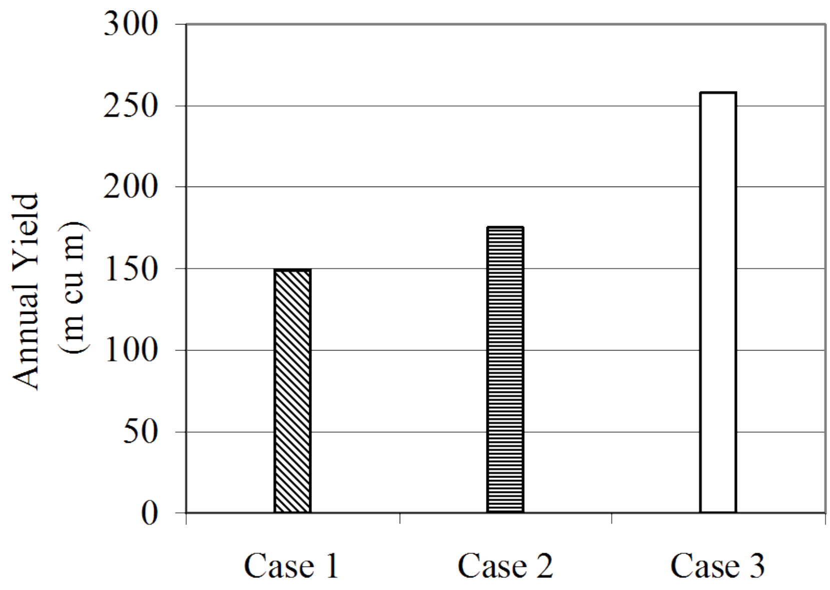

Figure 1. Comparison of Yield Model Results.

COMPARISON WITH RESULTS OF OTHER MODELS

The annual reservoir yield is also estimated with the commonly used methods of simulation and deterministic LP models for comparison with the yield model results. The simulation model is run for twenty two-year monthly inflow data in line with the yield model considerations for 100% and 75% annual project dependability. For the deterministic LP model the 100% and 75% annual dependable flow-year data are used. The lowest flow recorded is taken as the 100% annual dependable inflow assuming that future inflows will not be lower than the already recorded value. The annual reservoir yields obtained through this method are as given in Table 2.

Table 2. Comparison of Results of Annual Reservoir Yield from Three Models.

Models Studied	Annual Reservoir Yield (m cu m)		
	Case 1	Case 2	Case 3
Yield Model	149	175	258
Simulation	157	186	284
Deterministic LP Model	62	-	315

Examining the results of these models for 75% annual project dependability with variable yield during failure years (Case 3), which is comparable for these three methods, the annual reservoir yield obtained with the deterministic LP model is higher than that obtained

for simulation and yield model. The LP model result is higher since it uses a one-year 75% annual dependable flow data that may be attributed for the higher result. The result of the yield model is lower than the simulation result with a difference of 9.2%.
For the 100% annual project dependability (Case 1), the results of deterministic LP and yield models are both lower than the simulation result. But the yield model result is closer to the simulation with a difference of 5.3%.

The yield model estimate of the annual reservoir yield was on the whole lower compared to simulation results though not very significantly. The difference in the results of the yield model and simulation are attributable to the limitations of the model in terms of the assumptions made in estimating evaporation losses and within-year inflows. However, the yield model results could be regarded as reasonably acceptable given the advantages it offers as a simpler model. It avoids the inclusion of storage continuity and storage capacity constraints for every period of every year thereby greatly reducing the number of constraint equations and variables, and gives quick results considering the time involved in the trial-and-error approach of simulation method without requiring operating rule. Moreover, the yield model result could provide an initial value of annual reservoir yield for starting the simulation computations for defining the correct value of annual yield.

CROPPING PATTERN DETERMINATION

Irrigation planning, as an essential component of water management in irrigated agriculture, involves the determination of cropping pattern. Cropping pattern, among other factors, is affected largely by availability of irrigation water. In this analysis a cropping pattern for the above proposed reservoir project is worked out based on the annual reservoir yield estimate obtained with the yield model.

The following crop planning model is formulated using linear programming technique to determine optimal cropping pattern with the objective of maximising net returns from the crops subject to land and water constraints. Other resources are already considered in the computation of net returns. The net return for the crops is the difference between the selling price at the farmers end and the cost of production that includes cost of labour, fertiliser, irrigation, seeds, etc., at the field level.

The objective function is given as:

$$\text{Maximise} \sum_{k} B_k A_k \qquad (10)$$

Subject to:

(1) Land Area Constraint

$$\sum_{k} \lambda_{k,t} A_k \leq CCA \qquad \forall\ t \qquad (11)$$

$$A_k \geq C_{\text{min, k}} \qquad \forall\ k \qquad (12)$$

$$A_k \leq C_{\text{max, k}} \qquad \forall\ k \qquad (13)$$

(2) Water availability constraint

$$\sum_k W_{k,t} A_k = \eta y_t \qquad \forall\, t \qquad (14)$$

Where,

B_k	= net return per hectare from crop type k,
A_k	= the land area under crop type k,
$\lambda_{k,t}$	= land occupancy factor for crop k in time t,
CCA	= the total land area available for cultivation in ha,
$W_{k,t}$	= per hectare requirement of water by crop type k,
η	= irrigation conveyance efficiency,
y_t	= fraction of annual reservoir yield available in period t,
$C_{min,\,k}$	= minimum land area to be allotted for crop k in ha, and
$C_{max,\,k}$	= maximum land area to be allotted for crop k in ha.

The study considers the three Cases of water availability based on the annual reservoir yields estimated with the yield model discussed earlier. The land area available for irrigation is 36,544 ha. The percentage distribution of land area of the proposed project cropping pattern is used for limiting the maximum and minimum area under a given crop.

ANALYSIS OF CROP PLANNING MODEL RESULTS

The resulting cropping pattern is given in Table 3 and comparison of different cropping pattern results is shown in Figure 2.

Table 3. Results of Cropping Pattern.

Sl. No	Crop Type	Variable	Case 1		Case 2		Case 3	
			Area, ha	%	Area, ha	%	Area, ha	%
1	Paddy	A1	1279.05	3.50	1735.85	4.75	3288.98	9.00
2	Jowar/Maize	A2	3654.42	10.00	1242.50	3.40	5481.63	15.00
3	Cotton	A3	20.83	0.06	895.33	2.45	1827.21	5.00
4	Groundnut	A4	730.88	2.00	730.88	2.00	1096.33	3.00
5	Vegetables	A5	732.32	2.00	740.58	2.03	351.50	0.96
6	Fodder	A6	29.24	0.08	1827.21	5.00	1461.77	4.00
7	Sugarcane	A7	1461.77	4.00	1461.77	4.00	255.81	0.70
8	Wheat (HYV)	A8	511.62	1.40	844.17	2.31	5481.63	15.00
9	Wheat (Local)	A9	2192.65	10.00	2521.55	6.90	5481.63	15.00
10	Peas	A10	1461.77	4.00	1461.77	4.00	365.44	1.00
11	Berseem	A11	730.88	0.01	743.64	2.03	365.44	1.00
12	Vegetables	A12	734.35	2.00	730.88	2.00	225.71	0.62
13	Gram	A13	1461.77	4.00	2923.54	8.00	5426.19	14.85
14	Fodder	A14	913.61	5.34	730.88	2.00	2830.69	7.75
15	Vegetable	A15	969.78	1.00	1866.94	1.00	2604.24	7.13
TOTAL			16884.9	46.2	20457.5	55.98	36544.2	100.0

CASE 1: In this consideration the cropping pattern shows that only 56% (20,457.5 ha) of the total land area available could be brought under irrigation utilising 166.83 m cu m of the available 175.31 m cu m water. Eight of the crops are allotted the percentage distribu-

tion of area same as in the project cropping pattern, two crops (Groundnut and Gram) 66 and 72% respectively, one crop (Cotton) 50%, three crops (Paddy, Jowar and Local Wheat) 20-30% and one crop (Wheat-HYV) 10%.

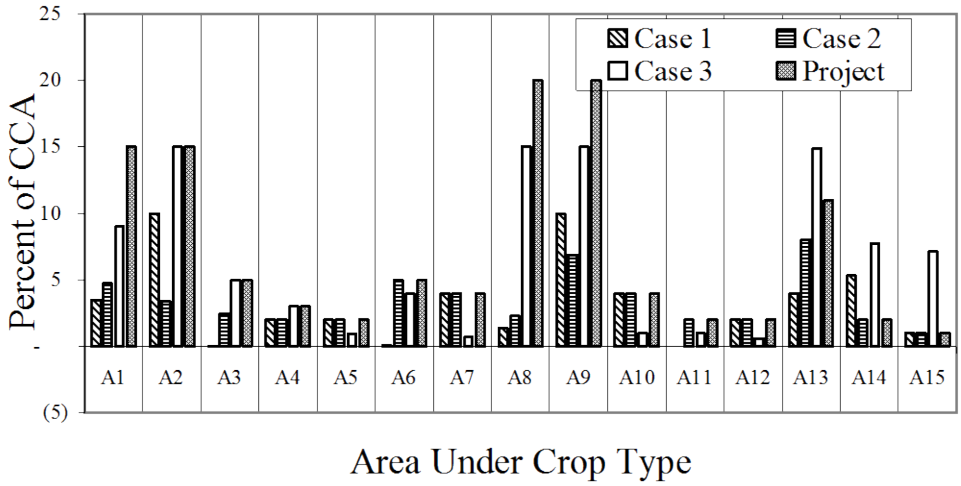

Figure 2. Comparison of Optimised and Proposed Project Cropping Pattern.

CASE 2: The 46.2% of available land is brought under irrigation utilising 141.2 m cu m of the available 149.2 m cu m water. Seven of the crops are allotted the percentage distribution of area as per project cropping pattern, two crops (Jowar and Groundnut) 65%, one crop (Gram) 35%, one crop (Local Wheat) 30%, one crop (Wheat-HYV) 7%, two crops (Cotton and Fodder) less than 1.5%.

CASE 3: The entire area is brought under irrigation using 236 m cu m of the available 257.86 m cu m of water. Six of the crops are allotted equal to or more than the percentage distribution of area as per project cropping pattern taking up 52% of the land area. Four crops (Paddy, Fodder and local and HYV Wheat) attain 60-80% of the project cropping pattern allotment, four crops (Kharif and Rabi Vegetables, Peas and Berseem) 25-50%, one crop (Sugarcane) 17%.

Examination of the cropping patterns for these Cases shows that the minimum area requirement is met largely for the crops grown during dry seasons when water requirement cannot be supplemented from precipitation.

BENEFIT–COST RATIO

In this analysis, benefit-cost ratio is used for further comparison of the Cases studied. The benefit-cost ratio is worked out using the gross annual benefit and the annual cost of the project. The project cost estimate of 1971 is Rs. 160.0 million. Annual cost of the project is determined considering 12% interest, 3% depreciation and 5% operation and maintenance costs. The value is projected to a present day level considering an inflation rate of 5%. The benefit-cost ratios for the various Cases studied are given in Table 4.

The benefit-cost ratios computed for the different Cases considered in the study show an acceptable result. The highest ratio of 1.99 is obtained for Case 3. The annual reservoir yield obtained in this Case is the highest since it does not commit an assured supply during failure years thereby making more water available for full irrigation coverage of the culturable command area during the successful years. However, the cropping pattern optimised for the more practical consideration of 75% project dependability with assured supply of 80% annual reservoir yield also shows good economic performance.

Table 4. Benefit-Cost Ratio for the Optimised Cropping Pattern.

Cases Studied	Annual Cost of Production (Rs.)	Annual Gross Benefit (Rs.)	Annual Cost of Project (Rs.)	Benefit-Cost Ratio
Case 1	77,247,956	172,128,868	138,302,156	1.24
Case 2	74,161,344	168,784,820		1.22
Case 3	114,881,582	275,442,410		1.99

CONCLUSION

The aim of this study was to estimate the optimal annual reservoir yield attainable for the given storage capacity analysing the recorded inflow data. Based on the annual reservoir yield estimated for the project, a cropping pattern was planned with the objective of maximising net returns from the crops considered for the study.

It is found out from the results of the study that the proposed reservoir with the given active storage capacity of 258 m cu m can provide a 100% dependable annual reservoir yield of 149.21 m cu m, a 75% dependable annual reservoir yield of 175.31 m cu m, with an assured supply of 80% of the annual reservoir yield during failure years, and 257.9 m cu m of 75% annual dependable reservoir yield with variable annual reservoir yield during failure years. A cropping pattern was planned for these annual reservoir yields, which offer 49.4%, 57.76% and 100% irrigation coverage respectively.

The 100% dependable safe annual reservoir yield (Case 1), as observed, is much lower to justify a meaningful cropping pattern. The 75% dependable annual reservoir yield (in Case 3) does not guarantee an assured minimal annual reservoir yield during failure years. Hence it can be concluded that the 75% dependable annual reservoir yield with an assured supply of 80% annual reservoir yield during failure years (Case 2) works out better for planning the project. The yield model provides a reasonably acceptable estimate of annual reservoir yield for planning a reservoir project.

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