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Optimal Reservoir Operation Of Gundlakamma Project

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Abstract: A reservoir operating policy is a sequence of release decisions in operational periods (such as months), specified as a function of the stage of the system. The state of the system in a period is generally defined by the reservoir storage at the beginning of a period and the inflow to the reservoir during the period. These reservoir release decisions are to be integrated with irrigation scheduling to obtain the best possible yields considering the crop yield response to water deficits.

In the present study, an optimal reservoir operation model integrating the reservoir releases to irrigation scheduling is developed by linear programming. The objective of the model is to minimize the reduction in yield of crops due to water deficits subject to constraints on storage, release, and mass balance of the reservoir. The decision variables are monthly releases to each crop grown under the project in a year. The model developed is applied to a case study of the Gundlakamma reservoir located in the Prakasam district of Andhra Pradesh, India. Inflows into the reservoir are obtained from the Thammavaram CWC station, and gross irrigation requirements of all crops grown under the left and right canals are determined. 75% dependable inflows are considered while deriving the optimal reservoir operating policy.

***Index Terms* -** Reservoir operating policy, Irrigation scheduling, Gundlakamma Reservoir, Minimize the reduction in yield of crops due to water deficits.

1.Introduction

Irrigated agriculture, particularly in arid and semiarid regions, is crucial for meeting the food requirements of India's growing population. Water is a significant factor limiting agricultural development, and efficient management of irrigation systems is essential. In India, water availability is limited and highly variable, causing strain on limiting resources. Proper irrigation planning can improve agricultural productivity by matching crop water demand with available resources. Irrigation scheduling is a crucial part of irrigation management, determining irrigation dates and water application based on root zone soil moisture dynamics.

A reservoir operating policy is a sequence of release decisions in operational periods, integrating with irrigation scheduling to maximize crop yields and minimize water deficits. Optimization algorithms have been developed to deriving reservoir operating policies, ensuring all planned objectives are met without compromising ecological water requirements. Optimizing storage reservoir operations aims to maximize benefits, crop yields, and releases, while considering constraints on releases, reservoir storage, and root zone storage.

1.1 Traditional Optimization Techniques

Linear programming and dynamic programming are two crucial optimization techniques used in reservoir operation. Linear programming is widely used in water resource planning and management due to its versatility and the availability of efficient solution algorithms and computer software packages. It is applicable to a wide variety of problems and is covered in books by Cooper and Cooper, Denardo, and Mays and Tuny. Dynamic programming, developed by Bellman in 1957, is restricted to specific forms of the objective function and is not precisely structured like linear programming. It involves decomposing a complex problem into simple sub-problems that are solved sequentially, transmitting essential information from one stage of computations to the next. Several dynamic programming models have been developed in the field of reservoir operation, providing a comprehensive approach to solving optimization problems.

2. INEAR PROGRAMMING

Linear programming (LP) is a technique used in various fields, including agriculture, industry, transportation, economics, health systems, behavioural and social sciences, and military. It offers efficient computational algorithms for problems with thousands of constraints and variables, making it the backbone of solution algorithms for Operational Research (OR) models.

2.1 Formulation of Model

- Water deficits in crops and the resulting water stress on the plant have an effect on crop evapotranspiration and crop yield.
- Water stress in the plant can be quantified by the rate of actual evapotranspiration (ETa) in relation to the rate of maximum evapotranspiration (ETm).
- When crop water requirements are fully met from the available water supply , then ETa=ETm;
- when water supply is insufficient, ETa<ETm.
- The manner in which water deficit affects crop growth and yield varies with the nature of crop and its growth stage. The reduction in yield with the water deficit is related as
- $1- (ya / ym) = ky (1-(Eta/ETm))$
- Where Ya=actual yield with available water.
  Ym=maximum yield that can be obtained when there is no limitation of water
  Ky=yield response factor.

2.2 Evapotranspiration

Actual Evapotranspiration

In the present study, all the water available (irrigation + rainfall) is assumed to be readily available to the crop and is considered as

$ETa = IR + Re$

Maximum Evapotranspiration

When water requirement of crop is fully met, the rate of evapotranspiration takes at its maximum rate and it is calculated as Etm

$ETm = \text{Max evapotranspiration}$

2.3 Constraints

The linear inequalities or equations or restrictions on the variables of a linear programming problem

Upper bound on ETa Constraint

- Actual Evapotranspiration for each crop at any time period t ETa c, t should be restricted to maximum evapotranspiration of the crop ETm c, t.
- $ETa_{c,t} \leq ETm_{c,t}$. $\forall$ t, c
- Here, Eta=IR + Re
- Then, constraint IR ≤ ETm-Re

Reservoir Storage Capacity

- Reservoir live Storage at the beginning of time period 't'
  i.e,. St should not exceed its maximum live storage of reservoir Smax.
  $S_t \leq S_{max} \quad \forall_t$
- Storage ≤ Storage capacity

Steady Storage Continuity

- Storage at the end of year should be equal to the storage at the beginning of the year.
  $S_{end} = S_{begining}$

Reservoir Storage Continuity

- Water balance of reservoir is governed by reservoir storage continuity equation.
  $St + Qt - Rt - Et = St + 1$

Where

St = active storage at the beginning of period *t*

Qt = inflow during period *t*

Rt = release during period *t*

Et = evaporation loss during period *t*.

3. SAILENT FEATURES OF THE PROJECT

Gundlakamma project is situated across river Gundlakamma near chinna mallavaram village in madhipadu mandal of prakasam
district of AP.

Storage at different levels:

At TBL = 109.286 MCM
AT FRL = 92.29 MCM
AT MDDL = 36.42 MCM

Capacity of Reservoir

At TBL = 109.286 mcm
At FRL = 92.29 mcm
At MDDL = 36.42 mcm
Live Storage Capacity = 55.87 mcm
Dead Storage Capacity = 19.85 mcm

4. USEFUL DATA AND CALCULTION

The C.W.C gauge station was established during 1978-79 and it has been functioning at Thammavaram since then. It is a Gauge-Discharge-Sediment-Water-Quality (GDSWQ) Station. The discharge data is observed using “FLOATS” method. The daily inflows at the CWC station for the period 1979-2000(22 years) have been procured & the same were processed & used in the present study. The net inflows are calculated monthly wise starting from the month June and are shown in Table 2. 75% monthly dependable flows are calculated by California method and shown in Table 2

TABLE 1 MONTHLY INFLOWS IN MCM FOR 22 YEARS

YEAR	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1978-79	0.544	1.565	3.911	11.037	3.786	5.997	1.983	1.357	0.869	0.283	0	14.448
79-80	0.587	1.62	1.147	14.206	2.569	9.133	4.092	1.609	0.73	0.423	0.34	0.203
80-81	1.956	0.407	1.113	1.623	4.092	4.106	2.62	2.555	0.826	0.792	0.421	1.697
81-82	0	1.19	1.113	7.471	10.044	4.91	2.544	2.127	0.521	0.17	0	0
82-83	0.192	0.541	0.06	3.139	7.878	1.363	2.912	2.026	0.686	0	0	0.172
83-84	0	2.529	3.47	10.116	9.115	6.406	5.36	4.391	1.185	0.225	0.132	0
84-85	0.109	0.63	0.412	1.479	5.597	3.676	4.067	5.151	1.727	1.412	0.634	0.167
85-86	0.419	0.78	0.994	3.101	10.513	3.367	4.782	4.499	2.056	0.27	0	0
86-87	0.364	0.27	1.522	2.869	4.727	7.471	3.085	3.575	1.814	1.1	0.035	0
87-88	0	0.447	0.908	0	12.442	20.859	1.81	1.291	1.029	1.282	0.647	0.003
88-89	0	0	2.992	7.54	3.078	2.513	6.257	3.228	1.615	2.774	1.044	0.029
89-90	0	3.929	0.653	3.07	6.618	8.06	4.281	3.139	2.619	1.634	1.589	6.059
90-91	1.036	0.088	0.855	4.84	18.77	10.02	6.78	3.484	1.279	1.171	0.98	0.215
91-92	1.542	0.62	0.298	4.78	5.279	19.15	5.52	4.469	1.939	0.63	0	0
92-93	0	0	0	0.24	3.157	15.45	4.121	3.51	2.93	2.039	1.023	0.666
93-94	0	0	0.32	4.033	11.188	3.43	10.205	4.06	2.649	1.37	0.962	0.475
94-95	0	0	0	0	8.959	17.16	3.598	5.123	2.153	1.335	0.718	2.715
95-96	0.069	2.676	2.775	1.845	4.136	2.624	3.57	4.83	2.586	2.303	1.18	0
96-97	1.601	0	0.93	3.83	18.871	9.21	7.82	7.98	3.504	1.464	1.444	0.193
97-98	0	0	0	17.164	6.92	9.647	10.188	4.474	2.935	1.446	0.321	0
98-99	0	0	0.52	5.541	18.14	10.216	5.506	5.447	3.786	2.302	0.717	0.99
99-2000	0.089	0.27	1.237	2.018	10.097	3.441	2.858	3.52	4.205	1.25	0.08	0

TABLE 2. 75% RELIABLE MONTHLY INFLOWS AND EVPORATION RATE

MONTHS	INFLOWS (MCM)	AVG.MONTHLY RATE OF EVAPORATION
JULY	0	152.4
AUGUST	8.858	152.4
SEPTEMBER	50.404	152.4
OCTOBER	116.188	152.4
NOVEMBER	96.84	101.6
DECEMBER	81.642	101.6
JANUARY	68.952	101.6
FEBRUARY	27.821	101.6
MARCH	10.928	228.6
APRIL	0.739	304.8
MAY	0	304.8
JUNE	0	228.6

TABLE 3. CROPPING PATTERN

Right Canal (ha)				Left Canal (ha)				
Kharif		Rabi		Kharif		Rabi		
Paddy	Maize	Pulses	Chilies	Paddy	Maize	Pulses	Chilies	Ground-nuts
2552	8780	2552	8780	5488	8420	5488	6420	9160

TABLE 4. KY, RE & ETM VALUES

MONTH		RIGHT CANAL				LEFT CANAL			
		KHARIF		RABI		KHARIF		RABI	
		PADDY	MAIZE	PULSES	CHILLIES	PADDY	MAIZE	PULSES	CHILLIES
JULY	KY		0.4				0.4		
	ETM		28.6				28.86		
	RE		13				13		
AUGUST	KY		0.4				0.4		
	ETM		88.55				88.55		
	RE		35				35		
SEPTEMBER	KY	1.1	1.5			1.1	1.5		
	ETM	142.88	113.7			142.88	113.7		
	RE	56	43			56	43		
OCTOBER	KY	2.4	0.2			2.4	0.2		
	ETM	128.22	83.66			128.22	83.66		
	RE	121	74			121	74		
NOVEMBER	KY	0.33			0.4	0.33			0.4
	ETM	107.1			21.42	107.1			21.42
	RE	26			8	26			8
DECEMBER	KY			0.05	0.4			0.05	0.4
	ETM			30.42	60.82			30.42	60.82
	RE			0	0			0	0
JANUARY	KY			0.4	0.8			0.4	0.8
	ETM			77.03	88.04			77.03	88.04
	RE			0	0			0	0
FEBRUARY	KY			0.2	0.8			0.2	0.8
	ETM			75.28	117.84			75.31	117.84
	RE			0	0			0	0
MARCH	KY				0.4				0.4
	ETM				97.65				97.65
	RE				0				0
APRIL	KY								
	ETM								
	RE								
MAY	KY								
	ETM								
	RE								
JUNE	KY								
	ETM								
	RE								
TOTAL AREA		2552	8780	2552	8780	5488	8420	5488	6420

4.1 Gross Irrigation Requirement of Crops

Gross irrigation Requirement of each crop at reservoir is calculated as follows:

- Net Irrigation Requirement is obtained by deducting effective rainfall from the crop evapotranspiration. NIRc,t = ETMc,t – REc,t
  Where $RE_{c,t}$ is the effective rainfall in period t and $ETM_{c,t}$ is the evapotranspiration.
- Gross irrigation requirement is obtained as
  GIRc,t $=A_c$ (NIRc,t / efficiency)

Monthly rate of evaporation and monthly rainfall data is obtained from the department of Irrigation, Government of Andhra Pradesh. Monthly rate of evaporation is shown in Table 5 Overall efficiency of irrigation is considered as 53%. Month wise Gross irrigation requirements of all crops are calculated . Total demand of water is shown in Table 6.

TABLE 5 EVAPORATION IN mm

Month	(mm)
January	101.6
February	101.6
March	228.6
April	304.8
May	304.8
June	228.6
July	152.4
August	152.4
September	152.4
October	152.4
November	101.6
December	101.6
Total	2082.2

TABLE 6 TOTAL DEMAND OF WATER

MONTH	DEAPH OF IRRIGTIO IN mm									OTHER RELEASES	TOTAL DEMAND
	RIGHT CANAL				LEFT CANAL						
	KHARIF		RABI		KHARIF		RABI				
	Paddy	Maize	Pulses	Chillies	Paddy	Maize	Pulses	Chillies	Groundnuts		
JULY		2.584				2.520				1.090	6.194
AUGUST		8.871				8.507				28.225	45.603
SEPTEMBER	4.183	11.706			8.996	11.226				1.090	37.201
OCTOBER	0.348	1.600			0.749	1.535				1.090	5.321
NOVEMBER	3.905			2.223	8.398			1.626	4.639	12.564	33.354
DECEMBER			1.465	10.075			3.150	7.367	14.017	1.090	37.164
JANUARY			3.709	14.585			7.976	10.664	18.069	1.090	56.094
FEBRUARY			3.625	19.521			7.798	14.274	5.741	1.090	52.050
MARCH				16.177				11.829		1.090	29.095
APRIL										1.090	1.090
MAY										1.090	1.090
JUNE										1.090	1.090

4.2 Objective Function

The objective function in present study is maximizing summation function of crop production measure of all crops grown. A penalty function is introduced in the objective function to minimize the spill from reservoir. If the term, Spill(SP) is not introduced into the objective function, it is possible for Spillt to be positive even when the reservoir does not reach the capacity at the end of the period, which is physically meaningless.

Maximize

$$Z = \Sigma_t \Sigma_c KY_{t,c} \left(\frac{ETa_{c,t}}{ETm_{c,t}}\right) - M\,SP_t$$

Where M is large arbitrary number

Minimize = $-7.698\text{x}10^{-3}\ X_1 - 0.0187\ X_2 - 3.081\text{x}10^{-3}\ X_3 - 0.0139\ X_4 - 4.517\text{x}10^{-3}\ X_5 - 0.0131\ X_6 - 2.39\text{x}10^{-3}\ X_7 - 1.643\text{x}10^{-3}\ X_8 - 5.192\text{x}10^{-3}\ X_9 - 2.656\text{x}10^{-3}\ X_{10} - 0.01867\ X_{11} - 6.576\text{x}10^{-3}\ X_{12} - 9.08\text{x}10^{-3}\ X_{13} - 6.788\text{x}10^{-3}\ X_{14} - 4.096\text{x}10^{-3}\ X_{15} - 7.698\text{x}10^{-3}\ X_{16} - 0.0187\ X_{17} - 3.081\ \text{x}10^{-3}\ X_{18} - 0.01386\ X_{19} - 4.51\ \text{x}10^{-3}\ X_{20} - 0.0131\ X_{21} - 2.39\ \text{x}10^{-3}\ X_{22} - 1.643\ \text{x}10^{-3}\ X_{23} - 5.19\ \text{x}10^{-3}\ X_{24} - 2.655\ \text{x}10^{-3}\ X_{25} - 0.0186\ X_{26} - 6.576\ \text{x}10^{-3}\ X_{27} - 9.086\ \text{x}10^{-3}\ X_{28} - 6.788\ \text{x}10^{-3}\ X_{29} - 4.096\ \text{x}10^{-3}\ X_{30} - 4.66\ \text{x}10^{-3}\ X_{31} - 9.86\ \text{x}10^{-3}\ X_{32} - 5.73\ \text{x}10^{-3}\ X_{33} - 6.02\ \text{x}10^{-3}\ X_{34} + 10000X_{48} + 10000X_{49} + 10000X_{50} + 10000X_{51} + 10000X_{52} + 10000X_{53} + 10000X_{54} + 10000X_{55} + 10000X_{56} + 10000X_{57} + 10000X_{58} + 10000X_{59}$

TABLE 7. DECISION VARIABLES

MONTH	**DEAPH OF IRRIGTIO IN mm**									**STORAGE (MCM)**	**SPILL (MCM)**
	KHARIF		RABI		KHARIF		RABI				
	Paddy	Maize	Pulses	Chillies	Paddy	Maize	Pulses	Chillies	Groundnuts		
JULY		X4				X19				X35	X48
AUGUST		X5				X20				X36	X49
SEPTEMBER	X1	X6			X16	X21				X37	X50
OCTOBER	X2	X7			X17	X22				X38	X51
NOVEMBER	X3			X11	X18			X26	X31	X39	X52
DECEMBER			X8	X12			X23	X27	X32	X40	X53
JANUARY			X9	X13			X24	X28	X33	X41	X54
FEBRUARY			X10	X14			X25	X29	X34	X42	X55
MARCH				X15				X30		X43	X56
APRIL										X44	X57
MAY										X45	X58
JUNE										X46	X59
NEXT YEAR JULY										X47	

4.3 Constraints Calculation

The linear inequalities or equations or restrictions on the variables of a linear programming problem

- **Upper bound on Irrigation release.**

X1 ≤ 86.88	X11 ≤ 13.42	X21 ≤ 70.66	X31 ≤ 26.84
X2 ≤ 7.22	X12 ≤ 60.82	X22 ≤ 9.66	X32 ≤ 81.1
X3 ≤ 81.1	X13 ≤ 88.04	X23 ≤ 30.42	X33 ≤ 104.55
X4 ≤ 15.6	X14 ≤ 117.84	X24 ≤ 77.03	X34 ≤ 33.22
X5 ≤ 53.55	X15 ≤ 97.65	X25 ≤ 75.31	
X6 ≤ 70.66	X16 ≤ 86.88	X26 ≤ 13.42	
X7 ≤ 9.66	X17 ≤ 7.22	X27 ≤ 60.82	
X8 ≤ 30.42	X18 ≤ 81.1	X28 ≤ 88.04	
X9 ≤ 77.03	X19 ≤ 15.86	X29 ≤ 117.84	
X10 ≤ 75.28	X20 ≤ 53.55	X30 ≤ 97.65	

- **Upper bound on reservoir storage.**

X35 to X47 ≤ 55.87

- **Steady Storage Continuity.**

$X_{35} = X_{47}$

- **Reservoir Storage Continuity.**

$$(1+a_t)S_{t+1} - (1-a_t)S_t + \sum_c A_c \frac{IR_{c,t}}{\eta \text{ x } 10^5} + SP_t = Q_t - A_0 e_t - OR_t$$

Where $\boldsymbol{a_t} = \frac{\boldsymbol{ae_t}}{\boldsymbol{2}}$

a is the water spread area (0.262) per unit live storage (million m^2/million cubic meter) above the dead storage level and e_t is the evaporation rate (m) in period 't'.

Ao = It is the water spread area (Million m^2) (10.9) corosprnding to dead storage
Q_t = Inflow entering into reservoir in time period t (MCM)
SP_t = Spill from reservoir (MCM)
$IR_{c,\,t}$ = Depth of irrigation (mm) to crop c in time period t
A_c = Area occupied by crop c in hectares
η = Efficiency of conveyance
e_t = Evaporation in m during time period t
OR_t = Other releases in mcm from reservoir like drinking water supply, etc (1.09)

1. – (1.02 X_{36}) + (0.98 X_{35}) - (0.165 X_4) - (0.158 X_{19}) $- X_{48} = 2.751$
2. - (1.02 $X_{37} - 0.98\, X_{36} + 0.165\, X_5 + 0.158\, X_{20} + X_{49}) = 21.0287$
3. $1.02\, X_{38} - 0.98\, X_{37} + 0.048X_1 + 0.166X_6 + 0.103X_{16} + 0.159\, X_{21} + X_{50} = 47.6431$
4. $1.02\, X_{39} - 0.98\, X_{38} + 0.048X_2 + 0.166X_7 + 0.103X_{17} + 0.159X_{22} + X_{51} = 113.436$
5. $1.013X_{40} - 0.987X_{39} + 0.048X_3 + 0.166X_{11} + 0.102X_{18} + 0.121X_{26} + 0.173X_{31} + X_{52} = 83.1762$
6. $1.013X_{41} - 0.986X_{40} + 0.103X_{23} + 0.121X_{27} + 0.048X_8 + 0.166X_{12} + 0.173X_{32} + X_{53} = 69.475$
7. $1.013X_{42} - 0.987X_{41} + 0.048X_9 + 0.1656X_{13} + 0.103X_{24} + 0.121X_{28} + 0.173X_{33} + X_{54} = 66.734$
8. $1.013X_{43} - 0.986X_{42} + 0.048X_{10} + 0.165X_{14} + 0.103X_{25} + 0.121X_{29} + 0.173X_{34} + X_{55} = 25.616$
9. $1.03X_{44} - 0.97X_{43} + 0.166X_{15} + 0.121X_{30} + X_{56} = 7.34$
10. -1.04$X_{45} + 0.96X_{44} - X_{57} = 3.674-1.04X_{46} + 0.96X_{45} - X_{58} = 4.412$

11. $-1.03X_{47} + 0.97X_{46} - X_{59} = 3.581$

5. RESULTS AND DISCURSION

The LP model created is applied to Gundlakamma reservoir project for the optimal reservoir operation for 75% reliable inflows. The objective of the model is to minimize the reduction in yield of all crops from the project considering the yield response to water deficit and reservoir storage continuity. LP model is solved in MATLAB and results obtained are shown in table 8.

TABLE 8

MONTH	Deapth of Release (mm)									STORAGE (mcm)	SPILL (mcm)
	RIGHT CANAL				LEFT CANAL						
	PADDY	MAIZE	PULSES	CHILLI	PADDY	MAIZE	PULSES	CHILLI	GROUND NUTS		
July		15.600				15.813				30.323	0.000
August		**0.018**				**0.021**				21.460	0.000
September	86.880	70.660			86.880	70.660				0.000	0.000
October	7.220	9.660			7.230	9.660				11.330	63.324
November	81.100			13.420	81.100			13.420	26.840	55.870	61.060
December			30.420	60.820			30.420	60.820	81.100	55.870	31.887
January			77.030	88.040			77.030	88.040	104.550	55.870	10.384
February			74.979	95.275			**0.044**	117.804	**0.000**	55.870	0.000
March				**0.032**				**0.024**		46.521	0.000
April										50.930	0.000
May										43.479	0.000
June										35.891	0.000

5.1 Discursion

From the table 2, it is observed deficit irrigation in the month of August, February and March and at the same time spills from the reservoir are observed in four months from October to January as shown in figure 2, This shows that existing reservoir capacity is not enough to meet the demand and to minimize the spills.

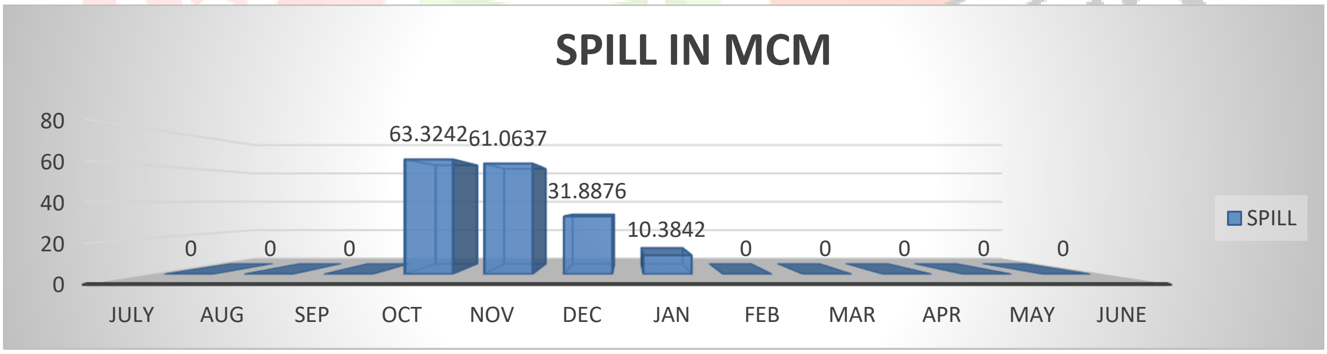


Fig. 2 Monthly Variations of Spills

The variation of reservoir storage at the beginning of each month is shown in figure 3. Carryover year storge of 30.327 MCM is to be maintained as initial storge for the steady state.

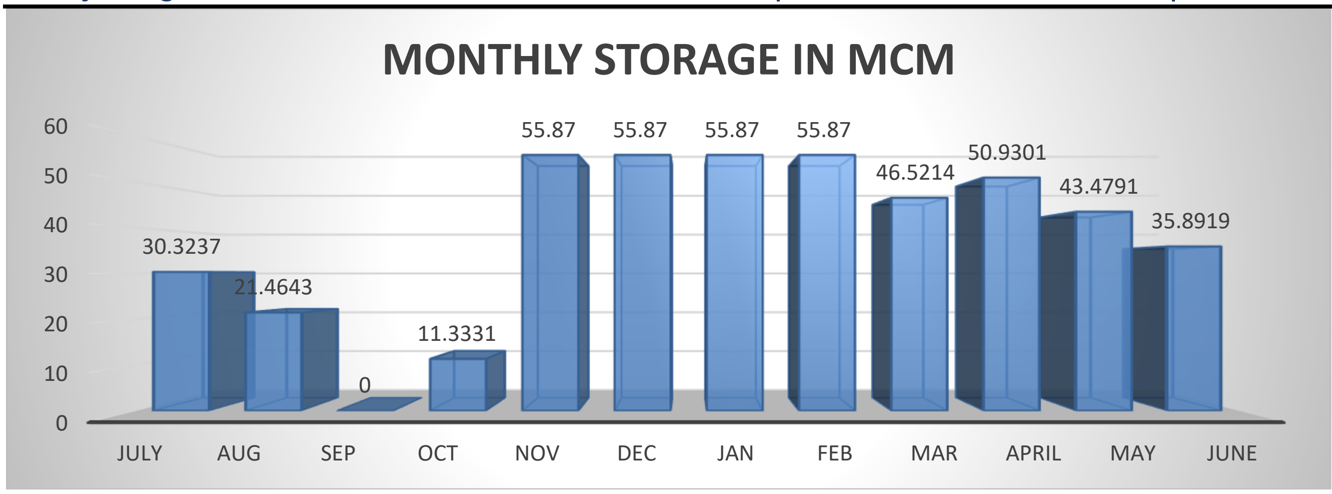
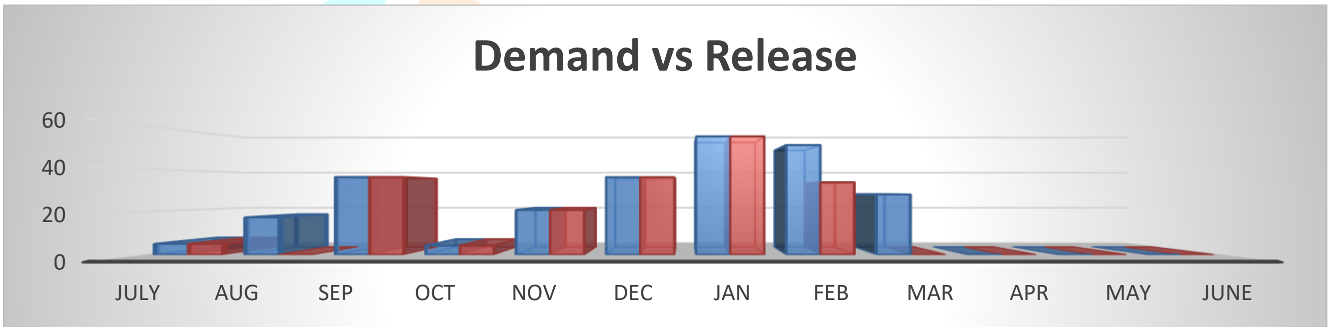


Fig. 3 Monthly Variations of Reservoir Storge.

The reservoir storage is getting depleted from July to September and the reservoir is full for four months continuously from November to February. As the inflows are greater than the storage capacity of reservoir, spills take place maintaining reservoir full from October to January.



	JULY	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE
DEMAND	5.1	17.37	36.11	4.23	20.79	36.07	55	50.95	28	0	0	0
RELEASE	5.1	0	36.11	4.23	20.79	36.07	55	33.66	0	0	0	0

Fig. 6.3 Graph Showing Demand and Supply

The above graph/Fig 4 shows monthly irrigation demand and irrigation release according to the policy, under 75% reliable inflows. The reservoir gave 25% deficit to its demand. It is clearly due to limited reservoir storage.