TRAINING COURSE

ON

RESERVOIR OPERATION

(UNDER WORLD BANK AIDED HYDROLOGY PROJECT)

Module 6

Reservoir Operation

for

Hydropower

BY

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RESERVOIR OPERATION FOR HYDROPOWER

1.0 INTRODUCTION

Hydropower is one of the major water uses. This forms an important part of a multi-purpose reservoir. Reservoir operation/regulation study is an essential part of water resources planning and management. The operating procedure (storage and releasing of water) for an individual reservoir may generally consist of the conventional operation rules used in planning working tables of a project reservoir. Sometimes a single rule curve may be also used.

1.1 BASIC RESERVOIR OPERATION CRITERIA

Basic Reservoir Operation Constraints

The basic reservoir operation criterion, Figure 1, is expressed in terms of simple equation, known as continuity equation and is as follows :

$$S_t = S_{t-1} + I_t + I'_t + P_t - El_t - O_t - O'_t \qquad \text{for all } t \qquad \ldots(1)$$

where S_{t-1} = Reservoir storage at the beginning of time t,
I_t = Inflow into reservoir during time t,
I'_t = Local inflow to the reservoir from surrounding area in time t,
P_t = Precipitation in the reservoir in time t,
El_t = Evaporation losses from the reservoir in time t,
O_t = Total out flow (release) from the reservoir in time t,
O'_t = Release to natural channel from reservoir in time t, and
S_t = Reservoir storage at the end of time t.

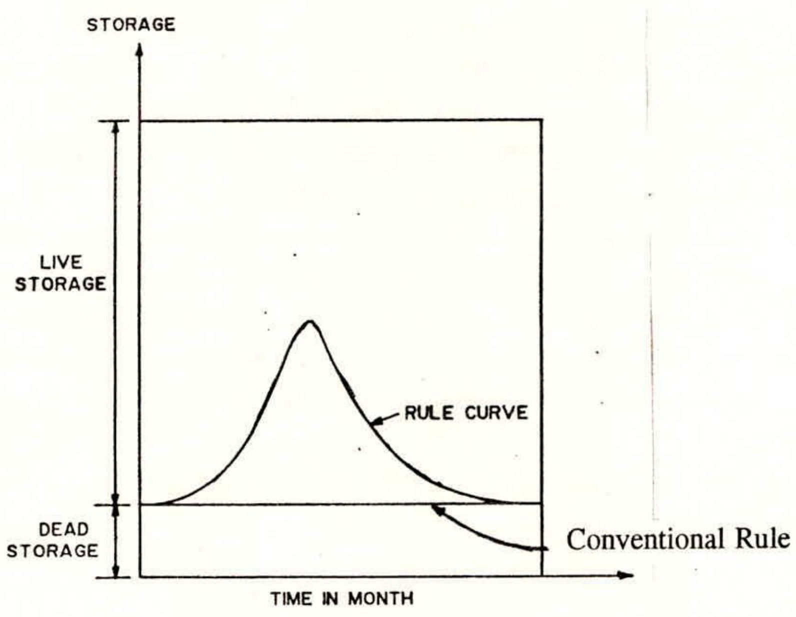

Fig. 1 Reservoir Operation Rule Curve

The above equation is subjected to the following constraints:

$$O_t \le S_{t-1} + I'_t + I_t + P_t - El_t - O'_t - Ymin_t \qquad \text{for all } t \qquad ...(2)$$

where $O_t = Oa''_t + Sp_t$ for all t ...(3)

Oa''_t = Release from reservoir to fulfill energy demand in time t, and

Sp_t = Reservoir spill in time t.

Water Balance of Reservoir

On yearly basis the water balance of the reservoir should be carried out as given below:

$$S_{12} - S_0 = (\Sigma I_t) + (\Sigma P_t) - (\Sigma El_t) + (\Sigma Oa''_t) + (\Sigma Sp_t) \qquad ...(4)$$

3.0 RESERVOIR OPERATION TECHNIQUES AND PRINCIPLES

3.1 Reservoir Operation with Conventional Rule

For reservoir operation the simplest operating rule is to supply all the water demanded, if available. In this situation, the release is almost independent of reservoir content and season. If there is sufficient water in the reservoir to meet the required releases, the reservoir empties. This simple phenomena is called the conventional rule (Fig. 1) for reservoir operation. This is with the aid of constraints (1), (2), (3) and a modified constraint (5) given by :

$$Yd = Ymin_t \le S_{t-1} \le Y \qquad \text{for all } t \qquad ...(5a)$$

3.2 Reservoir Operation with Single Rule Curve

Rule curve operation (Fig. 1), with constraints (1), (2), (3) and a modified (5) by adding Yr_t , may be such that as the storage of water in the reservoir decreases, restrictions may be imposed in the uses so that the demand falls and releases are lowered. The question comes in mind whether the water stored in the reservoir is to be used at present or to be retained for use during the possible droughts in future. A rule curve may be defined as a diagram showing reservoir storage requirements during the year. Reservoir operators are expected to maintain these levels as closely as possible while generally trying to satisfy various water needs downstream. If the reservoir storage levels are above the target or desired levels, the release rates are increased. Conversely, if the levels are below target levels, the release rates are decreased. These release rates may or may not be specified but will depend in part on any maximum or minimum flow requirements and on the expected inflow.

Hence, the constraint (4) is modified by incorporating the variable capacity up to Rule Curve level. Yr_t, of reservoir in time t, i.e.,

$$Yd = Ymin_t \le Yr_t \le S_{t-1} \le Y \qquad \text{for all } t \qquad ...(5b)$$

4.0 RESERVOIR REGULATION FOR HYDROPOWER

Regulation of a reservoir for hydropower can be done for the following cases :

(i) Regulation for dependable (firm) energy

(ii) Regulation for targeted energy

(iii) Regulation for maximum energy

The equations governing the power release O''_t and the turbine releases OT_t are given below:

(a) Dependable and Targeted Energy Regulations

$$\left.\begin{array}{l} Oa''_t < Od''_t \\ OT_t = Oa''_t \end{array}\right| \text{ for all t, if sufficient water is not available.}$$

$$\left.\begin{array}{l} Oa''_t = Od''_t \\ OT_t = Oa''_t \end{array}\right| \text{ for all t, if there is a reservoir spill.}$$

$$Oa''_t < OT_t \leq OTmax_t$$

(b) Maximum Energy Regulation

$$OT_t \leq OTmax_t$$

5.0 RESERVOIR REGULATION EXAMPLE

Table 1 shows operation of a reservoir for the regulation of a run of river hydroplant for maximum energy generation. Table 2 shows the regulation of an U/S storage reservoir for dependable energy. The hydroplant is located at the d/s reservoir with a fixed storage. Table 3 shows the regulation of a reservoir for annual targeted energy.

Notations

El_t	reservoir evaporation in time t
I_t	river inflow to reservoir in time t
I''_t	local inflow to reservoir from surrounding areas in time t
O_t	total water release from reservoir in time t
O'_t	release to natural channel (downstream riparian rights) from reservoir in time t
P_t	precipitation directly upon reservoir in time t
S_t	reservoir storage in the end of time t
Sp_t	reservoir spill in time t
t	any time

Y	total capacity of reservoir at maximum pool level
Ya_t	active capacity (Y - $Ymin_t$) of reservoir in time t
Yd	dead storage of reservoir
$Ymin_t$	variable capacity up to minimum pool level of reservoir in time t
Yr_t	rule curve (ideal storage) volume in time t
Oa''_t	release from reservoir to fulfill energy requirements in time t
Od''_t	energy demand from reservoir in time t
S_{t-1}	reservoir storage at the beginning of time t

Note: S_0 = 301.34 ha-m, Tail water level = 3m, e = 0.85 and plant capacity= 5MW.
$As = 5.7613(S)^{0.5}$, $EL = 0.0603\ As + 4.572$

6.0 REFERENCES

James, L.D. and Lee, R.E., 1971. Economics of Water Resources Planning, McGraw-Hill, New York.

Kuiper, E., 1965. Water Resources Development, Butterworth, Kent, England.

Srivastava, D.K., 1992a. "Development of a Computer Programme for Reservoir Operation", National Seminar on "Use of Computers in Hydrology and Water Resources", IIT, Delhi, New Delhi, Dec., Vol. II, pp.5-25 to 5-30.

Srivastava, D.K., 1992b. "Multipurpose Reservoir Operation. An Algorithm for Computer Programme", National Seminar on Computer Applications in Assessment, Development and Management of Water Resources, held at Centre for Water Resources Development and Management, Kunnamangalam (MBR), Calicut, Kerala.

Srivastava, D.K., and Bhattacharya, S.K., 1984. "Operation Rule Curve for Uduthorehalla Irrigation Reservoir". J. of IWRS, WRDTC, University of Roorkee, Roorkee.

Watershed Resources Management and Environmental Monitoring, 1981. Regional Training Course, University of Arizona, Tucson, Arizona, U.S.A.

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Table - 1 : Run of River Regulation for Maximum Energy Generation

Gross storage, Y = Nil   Dead storage Yd = Nil,   Live storage = Nil

Month t	Opening Balances S_{t-1}	Inflow I_t	Rain-fall P_t	Energy required/ dependable flow Od^*_t	Balance (6)= (2) +(3)+(4)-(5)	Mean storage (7)=(2)+(6)/2.0	Water spread (As_t)	Evaporation (EI_t) (9) $As_t = Ep_t k$	Head He_t ,	Closing Balance S_t	Spills Sp_t	Energy	
												Turbine Discharge OT_t	Generated EG_t
21	2	3	4	5	6	7	8	9	10	11	12	13	14
Jan	-	1.02	-	-	-	-	-	-	49	-	0	1.02	303957
Feb	-	1.10	-	-	-	-	-	-	49	-	0	1.10	327797
Mar	-	1.61	-	-	-	-	-	-	49	-	0.14	1.47	438055
Apr	-	1.19	-	-	-	-	-	-	49	-	0	1.19	354616
May	-	1.95	-	-	-	-	-	-	49	-	0.48	1.47	438055
Jun	-	3.06	-	-	-	-	-	-	49	-	1.59	1.47	438055
Jul	-	2.49	-	-	-	-	-	-	49	-	1.02	1.47	438055
Aug	-	1.30	-	-	-	-	-	-	49	-	0	1.30	387396
Sep	-	1.53	-	-	-	-	-	-	49	-	0.06	1.47	438055
Oct	-	1.33	-	-	-	-	-	-	49	-	0	1.33	396336
Nov	-	1.19	-	-	-	-	-	-	49	-	0	1.19	354616
Dec	-	0.91	-	-	-	-	-	-	49	-	0	0.91	271177
Total													

Note: In Col (13), OT_{max} = 1.47 cumecs, head in m, and energy in Kwhr.

Table-2 : Reservoir Regulation for Annual Dependable Energy

Gross Storage, Y = 1746 (U/s reservoir) | Dead storage, Yd = 0 | Live storage = 1746 | H = 100MW

Month	Opening Balance S_{t-1}	Inflow I_t	Rainfall P_t	Energy required/dependable flow Od^*_t	Balance (6) = (2) + (3) + (4) - (5)	Mean storage (7) = [(2)+(6)]/2	Water spread (As_t)	Evaporation (EI_t) $EI_t = Ep_t.K$	Head He_t in m	Closing Balance S_t	Spills Sp_t	Turbine Discharge OT_t	Energy Generated EG_t
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Aug	1746	8800	-	210	10336	-	-	-	235	1746	8590	8800	47855
Sep	1746	90	-	210	1626	-	-	-	235	1626	0	210	1142
Oct	1626	30	-	210	1446	-	-	-	235	1446	0	210	1142
Nov	1446	18	-	210	1254	-	-	-	235	1254	0	210	1142
Dec	1254	5	-	210	1049	-	-	-	235	1049	0	210	1142
Jan	1049	1	-	210	840	-	-	-	235	840	0	210	1142
Feb	840	0	-	210	630	-	-	-	235	630	0	210	1142
Mar	630	0	-	210	420	-	-	-	235	420	0	210	1142
Apr	420	0	-	210	210	-	-	-	235	0	0	210	1142
May	210	0	-	210	0	-	-	-	235	0	0	210	1142
Jun	210	0	-	210	0	-	-	-	235	0	0	210	1142
Jul	0	4200	-	210	3990	-	-	-	235	1746	2244	2454	13344
Total		13354		2520							10834		

(1) Od^*_t = Either Dependable flow Or ER_t /[9.8 C_f He_t h_t e], where ER_t = monthly energy demand, in kwhr, C_f = 0.003858 for this problem

(ii) OT_t = Turbine discharge, such that $Oa^*_t < OT_t < OTmax_t$, where $OTmax_t$ = max. turbine discharge,

$OTmax_t$ = H / [9.8 C_t He_t e], where H = power plant capacity in KW. $OTmax_t$ = 100 x 1000 / [9.8 x 0.003858 x 235 x 0.85] = 13241 hec-m.

(iii) Ep_t = pan evaporation in m., k = pan coefficient. In case of runoff river plant $OT_t < OTmax_t$

(iv) Check 1746 - 1746 = 13354 - (2520 + 10834) = 0, Volume units in hec-m, Energy units in Mwhr, Head in meters

Table : 3 - Reservoir Regulation for Annual Targeted Energy

Ya = 968 ha-m

t	S_{t-1} (ham)	I_t (ham)	P_t (ham)	As_t (ha)	El_t (ham)	Net water (ham)	EL_t (m)	He_t (m)	Energy Demand			Energy Release Oa^*_t (ham)	Sp_t (ham)	$O_t = oa^*_t + Sp_t$ (ham)	OT_t (ham)	EC_t (Mwhr)	S_t (ham)	Energy surplus/deficit
									% of total energy demand	In Mwhr	Od^*_t (ham)							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Jan	301.34	245	6.9	100.01	1.69	551.55	10.60	7.60	0.12	12	68.24	68.24	0	68.24	68.24	12	483.31	0
Feb	483.31	613	7.6	126.66	2.57	1101.34	12.21	9.21	0.10	10	46.92	46.92	86.42	133.34	133.34	28.42	968	+18.42
Mar	968	6.9	1.1	179.25	5.43	970.57	15.38	12.38	0.06	6	20.95	20.95	0	20.95	20.95	6	949.62	0
Apr	949.62	0	2.0	177.54	8.75	942.87	15.28	12.28	0.05	5	17.60	17.60	0	17.60	17.60	5	925.27	0
May	925.27	0	0.6	175.25	14.27	911.60	15.14	12.14	0.07	7	24.92	24.92	0	24.92	24.92	7	886.68	0
Jun	886.65	0	0	171.55	17.64	869.04	14.92	11.92	0.01	10	36.25	36.25	0	36.25	36.25	10	832.79	0
Jul	832.79	0	0	166.26	19.00	813.79	14.60	11.60	0.11	11	40.98	40.98	0	40.98	40.98	11	772.81	0
Aug	772.81	0	0	160.16	16.48	756.33	14.23	11.23	0.09	9	34.63	34.63	0	34.63	34.63	9	721.70	0
Sep	721.70	0	0	154.77	14.52	707.18	13.90	10.90	0.05	5	19.82	19.82	0	19.82	19.82	5	687.36	0
Oct	687.36	0	1.4	151.05	9.86	678.90	13.68	10.68	0.05	5	20.23	20.23	0	20.23	20.23	5	658.67	0
Nov	658.67	0	2.1	147.86	4.94	655.83	13.49	10.49	0.09	9	37.08	37.08	0	37.08	37.08	9	618.75	0
Dec	618.75	0	11.4	143.31	2.42	627.73	13.21	10.21	0.11	11	46.56	46.56	0	46.56	46.56	11	581.17	0
Total		864.9	33.1		117.57									500.60		118.42		

Check $\Sigma I_t - \Sigma O_t = \Delta S$, L.H.S = 864.9 + 33.1 - 117.57 - 500.60, R.H.S. = 581.17 - 301.34 = 279.83