STATE OF ART REPORT

Scientific Contribution
No.: INCOH/SAR-9/95

REAL TIME RESERVOIR OPERATION

D.K. Srivastava

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA
December, 1995

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Ministry of Water Resources, Govt. of India)

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PREAMBLE

It has been estimated that the total world population will increase from 4.5 billion in 1980 to about 6.5 billion by the year 2000, with the most rapid growth in the developing countries. By that time, the countries within the humid tropics and the other warm humid regions will represent almost one-third of the total world population. This proportion will continue to rise in the twenty-first century. The developing and under-developed countries thus quite clearly are the regions facing potentially serious water problems. Hence, it is urgent to question as to whether the fields of hydrology and water resources management have the appropriate methods in place to meet the rising demands that will be made on the water resources. Hence it becomes very important and expeditious to review and update the state-of-art in different facets of hydrology and component processes. This calls for compiling and reporting present day technology in assessment of water resources and determining the quality of these water resources.

The Indian National Committee on Hydrology is the apex body on hydrology constituted by the Government of India with the responsibility of coordinating the various activities concerning hydrology in the country. The committee is also effectively participating in the activities of Unesco and is the National Committee for International Hydrological Programme (IHP) of Unesco. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the committee invites experts in the country to prepare these reports on important areas of hydrology.

A multipurpose reservoir serves several requirements like water supply, irrigation, power generation, navigation, recreation, flood control etc. The performance of a reservoir can be studied in terms of physical outputs and economics benefits achieved, hence, it is necessary to construct an operating procedure i.e. a set of rules for storing and releasing water from a reservoir. In this state-of-art report the real time reservoir operation has been focussed. Mainly the basic reservoir operation criteria, operation techniques, algorithms which can be used have been discussed giving actual case studies.

The Indian National Committee on Hydrology with the assistance of its erstwhile Panel on Water Resources Systems has identified this important topic for preparation of this state-of-art report and the report has been prepared by Prof. D.K. Srivastava, Department of Hydrology, University of Roorkee, Roorkee. The guidance, assistance and review etc. provided by the erstwhile Water Resources Systems Panel are worth mentioning. The report has been compiled and finalised by Dr. K.K.S. Bhatia, Member Secretary of the Indian National Committee on Hydrology.

It is hoped that this state-of-art report would serve as a useful reference material to practicing engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilization of the water resources of the country.

(S.M. Seth)
Executive Member, INCOH
& Director, NIH

Roorkee

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INTRODUCTION

A multipurpose reservoir serves several requirements, i.e., water supply, irrigation, electric power, navigation, recreation, water quality improvement, flood control, and fish and wild-life enhancement.

Since the performance of a reservoir is studied in terms of physical outputs and economic benefits achieved, it is necessary to construct an operating procedure (a set of rules for storing and releasing water from a reservoir).

A variety of operating policies are in use at the present time. These operating policies vary from those that only define each reservoir's target levels (and provide no information or guidance on what to do if maintaining these levels become impractical or impossible), to those that define general guidelines, i.e., how much water to withdraw or release for all possible combinations of storage conditions). There are three basic techniques of reservoir operation for which the operation guidelines are discussed.

The operation of most multiple-reservoir systems reflects the fact that there are both conflicting and complementary multiple purposes served by the water stored in and released from reservoirs. These purposes can include.

(1) Water supply for municipal, industrial and agricultural (irrigation) needs from lakes and streams.

(2) Water quality Improvement by releasing water of higher quality upstream to dilute and transport down-stream wastes.

(3) Flood control through the provision of available storage capacity during periods when floods are possible and maximum use of down stream channel capacities during periods of high runoff to reduce the likelihood of flood damage.

(4) Hydropower production by operating reservoirs so as to minimize loss of energy and power requirements.

(5) Navigation by insuring sufficient depth of water in navigation channels and sufficient water supply for lockages.

(6) Recreation whose benefits, while sometimes difficult to quantify in monetary terms, are nonetheless often present if appropriate pool levels and limits on levels fluctuations are maintained.

(7) Fish and wildlife enhancement through the maintenance of desirable pool level or flows during critical periods in the year for greater fish and wildlife production and fishing and hunting benefits.

Political and economic decisions usually dictate whether a single purpose or multipurpose reservoir is to be constructed. It is usually more economical to construct a reservoir capable of meeting several requirements rather than one. Also, it is possible in many instances to meet more than one demand with a fixed storage. For example, a given volume of storage may provide flood control during the rainy season, but that the same volume may provide water supply needs during the dry season. If hydroelectric power is being generated, there may be constraints placed on the operation of the reservoir pool to maintain the required head of water. Sometimes the demands for water are competitive for the same time period. Storage volumes in the reservoir must then be allocated to meet these competitive demands.

The operating procedure for an individual reservoir may generally consist of the conventional operation rules used in preparing working tables of a project reservoir. In this reservoir operation technique the simplest operating rule is to supply all the water demanded, if available.

Assuming that it is possible to define ideal storage levels and down stream releases and/or diversions for every day, week or month throughout the year (i.e., assuming there exists a set of storage and release values that best satisfies all water users), reservoir operating procedures are needed and are used to guide operators when it is not possible to satisfy these ideal conditions. The purpose of operating policies is to distribute any necessary deviations from ideal conditions in a manner that satisfies mandated laws or regulations and/or that minimizes the total perceived discomfort or hardship to all water users in the system. Ideal storage volumes or levels in individual reservoirs are typically defined by rule curves. When conditions are not ideal, operating policies or rule of system operation define what should be done for various combinations of system states and hydrologic conditions. Together, rule curves and rules of system operation define desired storage volumes or levels, reservoir releases and diversion quantities. Ideal storage volumes or levels usually vary throughout the year, but do not vary from year to year.

Several examples of use of single rule curves for reservoir operation depending on the type of reservoir regulations, are presented in (Kuiper, 1965). It also discusses how a rule curve can be derived at. Case studies by (Srivastava and Bhattacharya, 1964) on Uduthorehalla reservoir using single rule curve, by (Ghushinge, 1984) on multiple reservoir system in Narmada, by (Din Dayal, 1986) on a multipurpose dam in northern India, by (Mahanta, 1989) on Sardar Sarovar reservoir, and by (Mohanty, 1992) on Bargi reservoir are some of the examples of multi rule curves reservoir operation.

Sometimes, operation rules are often defined to include not only storage target levels, but also various storage allocation zones. These storage zones may vary throughout the year. A paper by (Loucks, and Sigvaldason, 1980) and a course manual (Watershed Resources Management and Environmental Monitoring, 1981) have discussed the principles involved in reservoir operation by zoning or partitioning.

RESERVOIR OPERATION QUESTIONS

These reservoir operation techniques answer some basic reservoir operating questions. There are six basic reservoir operating questions (James and Lee, 1971):

(1) **Use of Flood Storage** : Whether flood inflows should be stored to reudce current damages or released to provide additional storage space in case new rains produce even greater flows (i.e., release of flood waters during floods from the flood storage space).

(2) **Use of Total Storage** : Whether storage space should be filled to save water for beneficial use or emptied to contain potential floods (i.e., whether to use flood storage space temporarily for conservation during flood or vise versa).

(3) **Release of Stored Water** : Whether water stored within the reservoir should be released for present use or retained for use during possible future droughts (i.e., release of currently stored water in respect of time. Conserve or not?).

(4) **Use of Available Water** : How the water released from the reservoir be divided among the various potential uses (i.e., release of currently available water in respect of current uses. As per Priority?).

(5) **Release Elevation** : Whether the release water should be taken from near the surface or from some elevation deeper within the reservoir.

(6) **Release by Reservoir** : How much of the water to be released for beneficial use should come from each reservoir in which water is stored (i.e., release of water among reservoirs).

Table 1 gives various situation parameters which govern these operating questions.

Table - 1 : Governing Situation Parameters for Reservoir Operation

Basic Parameters	Type of Situation Parameters	Operating Questions 1	2	3	4	5	6
Storage	Total available flood storage space	G	-	-	-	-	-
	Amount of flood storage currently available	-	G	-	-	-	-
	Amount of water currently stored in flood space	G	-	-	-	-	-

Basic Parameters	Type of Situation Parameters	Operating Questions 1	2	3	4	5	6
	Amount of water currently in reservoir*/reservoirs**	-	G(*)	G(*)	-	-	G(**)
Inflow	Forecasted or expected inflow (during floods+/during current, drawdown period++/ as a general+++) in reservoir*/ reservoirs**	G(+*)	-	G(++*)	-	-	G(+++**)
	Magnitude of flood threat	-	G	-	-	-	-
	Probability of continued rainfall by amount and duration by season	G	-	-	-	-	-
Economic	Relationship between release rate and D/S flood damage	G	-	-	-	-	-
	Value of stored water in other uses	-	G	-	-	-	-
	Value of water in alterative uses	-	-	G	-	-	-
	Demand curves of water in each of the uses	-	-	-	G	-	-
	Cost of transmitting water from each reservoir to the point of use	-	-	-	-	-	G
Water Quality	Temperature and quality of water at various elevations in reservoir	-	-	-	-	G	-
	Consequence of alternative levels of water quality	-	-	-	-	G	-
	Consequences of releasing waters of various temperatures or qualities to D/S channel	-	-	-	-	G	-
Number of Res-ervoirs	Other reservoirs in combinations	G	-	-	-	-	-

Note: G - Governing parameter

RESERVOIR PROJECT TYPE, REGULATION, AND OPERATION TECHNIQUES

A brief description of various types of reservoir regulations and in each case the likely reservoir operation technique and the policies generally adopted in practice for various types of water resources projects is given in Table -2.

Table - 2 : Reservoir Regulation Vs Reservoir Operation Technique

Object	Type of Regulation	Reservoir Operation Technique			Given Reservoir Storage	Policy
		Con-ventio-nal Rule	Single Rule Curve	Zoning (Parti-tion-ing)		
1	2	3	4	5	6	7
Irrigation	Case-I Dependable Project Diversion	Yes	-	-	S	a. To irrigate 'Normal Area' for dependable flow (firm flow) b. Entire storage used to irrigate 'Normal Area'
	Case-II Maximum Project Diversion	-	Yes	-	S	a. To irrigate 'Larger than Normal Area' for a smaller dependable flow (less than as in Case-I) b. Upper portion of storage (above Rule Curve) to irrigated 'Larger than Normal Area' and lower portion of storage (below Rule Curve) to irrigate 'Smaller than Normal Area'
Hydro-power	Case-I Dependable (All Hydro)	Yes	-	-	S_1	a. Hydroplant to supply dependable flow during low river flows b. Hydroplant placed at the base of the load (any shortfall will be supplied by other source)

1	2	3	4	5	6	7
	Case-II Dependable Flow (Hydro -steam)	Yes	-	-	$S_2 < S_1$	a. Hydroplant to supply a smaller dependable flow (less than as in Case-I) during low river flows. b. Hydroplant at the peak and steamplant placed at the base of the load (during low river flows) c. Dependable flow to be calculated on the basis of firm capacity of hydroplant
	Case-III Maximum Energy Output (Hydro -steam)	-	Yes	-	$S_2 + S_1$	a. Remarks (a) through (c) same as in Case - III b. S_3 gives high additional energy (Maximum energy output) c. Upper portion of storage (above Rule Curve) to be used for releasing more than firm energy targets d. Lower portion of storage (above Rule Curve) to be used for releasing upto the firm energy targets
Multi-purposes	Case-I Conservation Purposes	-	Yes	-	S'	a. Upper portion of storage (above Rule Curve) to be used for releasing more than firm targets b. Lower portion of storage (below Rule Curve) to be used for releasing upto the firm targets
	Case-II Conservation and Flood Control	-	-	Yes	S"	Partitioning of storage a. Zone-I: Flood Control Zone (Upper storage) b. Zone-II: Conservation Zone (below Zone-I) (with portion of Zone-II as Buffer space) c. Variable zone boundaries to be fixed based on seasons (i.e., periods of Floods, High flows, Normal flows, Low flows, and Driest flows) d. Zone-III: Inactive Zone (Lowest Storage).

BASIS RESERVOIR OPERATION CRITERIA

I. 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 :

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

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,

EI_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.

The above equation is subjected to the following constraints.

$$O_t \leq S_{t-1} + I'_t + I_t + P_t - EI_t - O'_t - Ymin_t \quad \text{for all } t \quad (2)$$

Where, $O_t = Or'_t + Oa_t + Oa''_t + Sp_t \quad$ for all t $\quad$ (3)

Or'_t = Actual release for water supply from reservoir in time,

Oa'_t = Actual irrigation release from reservoir in time t,

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

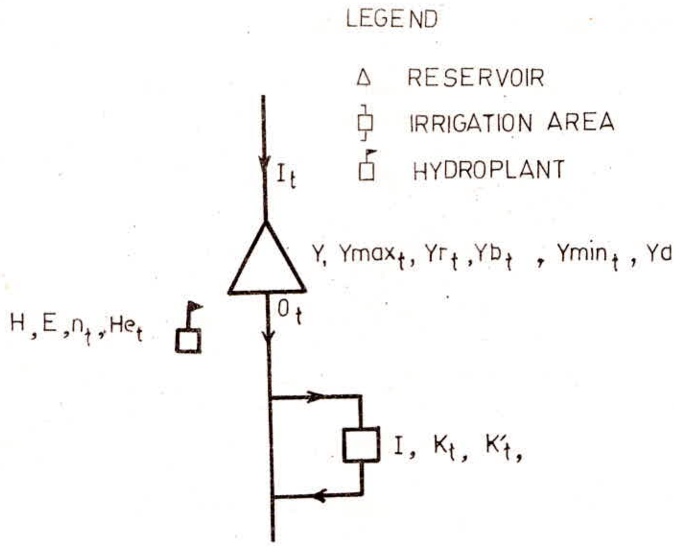

Fig 1 (a) Line Diagram of Reservoir System

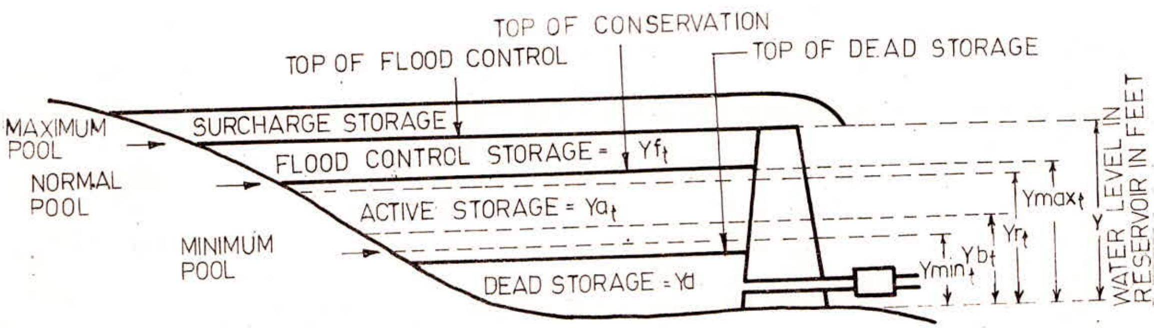

Fig 1 (b) Various Reservoir Storages

Fig. 1: Reservoir Description

Sp_t = Reservoir spill in time t.

$$Yd \leq Ymin_t \leq S_{t-1} \leq Ymax_t \leq Y \qquad \text{for all } t \qquad (4)$$

Where,

$Ymin_t$ = Minimum storage of reservoir in time t,
$Ymax_t$ = Maximum storage of reservoir in time t,
Y = Gross capacity of reservoir, and
Yd = Dead storage capacity of reservoir

II. Water Balance of Reservoir :

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

(i) Opening balance, S_o

(ii) Total inflows $(\Sigma I_t + \Sigma I'_t)$ =
Total rainfall (ΣP_t) = --------------------
Total input into reservoir =

(iii) Total evaporation losses $(\Sigma\ EI_t)$ =
Total Downstream rights releases $(\Sigma\ O'_t)$ =
Total water supply releases $(\Sigma\ Or'_t)$ =
Total irrigation releases $(\Sigma\ Oa'_t)$ =
Total energy releases $(\Sigma\ Oa''_t)$ =
Total reservoir spill $(\Sigma\ Sp_t)$ = --------------------
Total output from reservoir =

(iv) Closing balance, S_{12} =

Check:
Change in Reservoir Storage = (Total input into reservoir - Total output from reservoir)

or $S_{12} - S_0 = [(\Sigma I_t)+(\Sigma I'_t)+(\Sigma P_t)] - [(\Sigma\ EI_t)+(\Sigma O'_t)+(\Sigma Or'_t)+(\Sigma Oa'_t)+(\Sigma Oa''_t)+(\Sigma Sp_t)]$

RESERVOIR OPERATION TECHNIQUES AND PRINCIPLES

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, (Figure 2) for reservoir operation. This is with the aid of constraints (1), (2), (3) and a modified constraint (4) given by :

$$Yd = Ymin_t \leq S_{t-1} \leq Y \qquad \text{for all } t \qquad (4a)$$

Reservoir Operation with Single Rule Curve :

Rule curve operation (Figure 2), with constraints (1), (2), (3) and a modified (4) 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 upto Rule Curve level, Yr_t, of reservoir in time t, i.e.,

$$Yd = Ymin_t \leq Yr_t \leq S_{t-1} \leq Y \qquad \text{for all } t \qquad (4b)$$

Reservoir Operation With Zoning or Partitioning

In a multipurpose reservoir when the demands for water are competitive for the same time period, storage volumes in the reservoir must then be allocated to meet these competitive demands. This partitioning process involves both the determination of required volumes, and establishing operating rules to specify how the reservoir is to be managed. The elevations of the various zones are used as guides for operation and can vary seasonally (Watershed Resources Management and Environmental Monitoring, 1981), Figure 2.

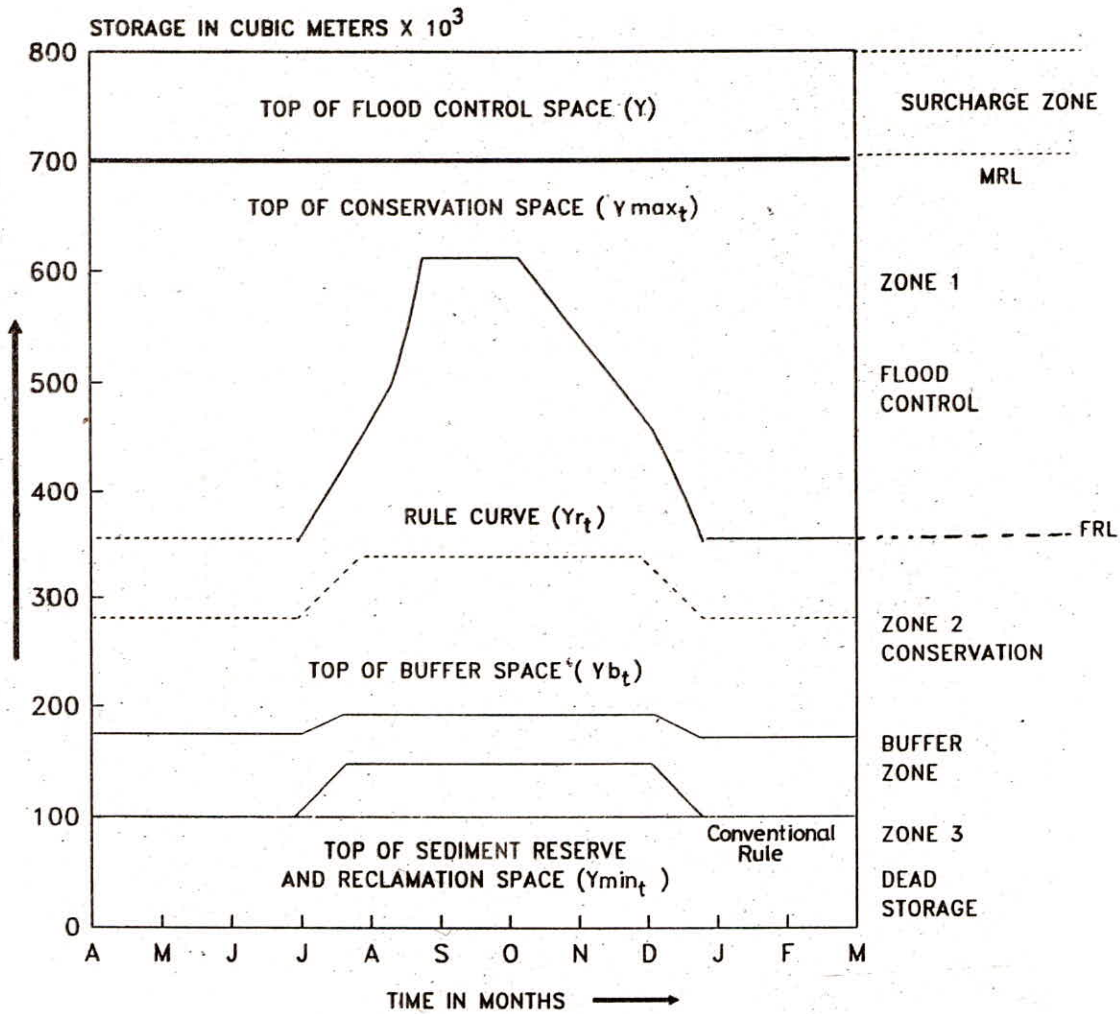

Fig. 2 Operational zones and rule curve illustrating seasonally varying storage requirements of a multipurpose reservoir

The following five zones might be considered :

(1) **Surcharge Zone** - the storage above the flood control zone associated with actual flood damage. Top of the flood control pool is used to maintain the integrity of the reservoir. Reservoir releases are usually at or near their maximum to prevent the dam from collapsing when the storage volume is within this zone.

(2) **Flood Control Zone** - a reserve for storing large inflows during periods of abnormally high runoff. The flood control zone would be evacuated of water at a time corresponding to the flood season. The reservoir would then be kept at the top of conservation space (bottom of flood control space) to provide sufficient storage to control flooding. Once the pool elevation is in this zone, the reservoir is operated to release the maximum amount of water without causing flooding ideally, this would coincide with bankfull conditions down-stream.

(3) **Conservation Zone** - the zone of storage from which various water based needs are satisfied. The ideal storage volume or level is normally located within this zone. A system of priorities may be established within this zone to insure that vital water will be met.

(4) **Buffer Zone** - the storage beneath the conservation zone entered only in abnormally dry periods. When storage volumes are within this zone, releases are restricted temporarily to satisfy essential (high priority) needs only.

(5) **Inactive Zone** - the dead storage beneath the buffer zone which would if possible, be entered only under extremely dry conditions. Reservoir withdrawals are an absolute minimum. This zone contain enough space to trap and retain sediment over the life of the project.

Hence, the constraint (4) is modified by incorporating the storage capacity for conservation purposes, $Ymax_t$, i.e.,

$$Yd \leq Ymin_t \leq S_{t-1} \leq Ymax_t \leq Y \qquad \text{for all } t \qquad (4c)$$

Also, If $S_{t-1} \leq Yb_t$ then $Oa'_t = Oa''_t = 0$ for all t (5)

and If $S_{t-1} > Yb_t$, then releases are to be made as per priority of uses, for all t.

ALGORITHM FOR RESERVOIR OPERATION

For a multipurpose project (Srivastava, 1992a) to serve irrigation, hydropower, municipal and industrial use, and flood control, a reservoir operation algorithm can be formulated based on the principles given earlier. A project may demand a systematic supply of water to the various purposes. Accordingly, provisions can be made for the following: First priority is given to the down-stream municipal and industrial uses. After serving the required demand, if water is available, it serves for irrigation use. There is a provision that power may be generated from the downstream municipal and industrial water use as well from the irrigation water. Energy deficits can be made up, if more water is available. The detailed working table for reservoir operation is given in Appendix-I. A detailed algorithm has been developed on the basis of the above principles (Appendix-II). A computer programme can be developed on this basis (Srivastava, 1992b).

Some case studies of reservoir operation are given in Appendices III, IV, and V.

NOTATIONS USED IN THE REPORT

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 beginning 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 ($Ymax_t$ - $Ymin_t$) of reservoir in time t
Yd	dead storage of reservoir
Yf_t	flood storage capacity ($Y-Ymax_t$) of reservoir in time t
$Ymax_t$	variable capacity upto normal pool level of reservoir in time t
$Ymin_t$	variable capacity upto minimum pool level of reservoir in time t
Yr_t	rule curve (ideal storage) volume value in time t
Oa'_t	actual irrigation release from reservoir in time t
Oa''_t	additional release from reservoir to fulfill energy requirements in time t
Od'_t	irrigation demand from reservoir in time t
Od''_t	energy demand from reservoir in time t
Or_t	water supply demand from reservoir in time t
Or'_t	actual release for water supply from reservoir in time t

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APPENDIX-I

WORKING TABLE FOR RESERVOIR OPERATION

Item
Time, t (1)
Opening Balance, S_{t-1} (2)
Water Spread, As_t (3)
Evaporation, El_t (4)
Release to Natural Channel, O'_t (5)
Elevation, EL_t (6)
Head on Turbine, He_t (7)
Inflow, I_t (8)
Local Inflow, I'_t (9)
Rainfall, P_t (10)
Net Water Available (11)=(2)-$Ymin_t$+(8)+(9)+(10)-(4)-(5)
Water Supply Demand, Or_t (12)

Actual Water Supply Release, Or'_t, RLS (1)
(13)=Smaller of (11) or (12)

Balance
(14)=(11)-(13)

Irrigation Demand/Dependable Flow, Od'_t
(15)

Actual Irrigation Release, Oa'_t, RLS (2)
(16)=Smaller of (14) or (15)

Balance
(17)=(14)-(16)

Energy Demand/Dependable Flow, Od''_t
(18)

Energy Generated From Release Oe_t, if any
(19)

Additional Release For Energy, Oa''_t, RLS (3)
(20)*=Smaller of (17) or [(18)-(19)]

Energy Generated From Oa''_t
(21)

Total Energy Generated Upto Now From Oe_t & Oa''_t
(22)=(19)+(21)

Balance
(23)=(17)-(20)

Reservoir Spill, Sp_t, RLS (4)
(24)=$Ymin_t$ + (23)-$Ymax_t$

Total Release, O_t
(25)=(13)+(16)+(20)+(24)

Total Turbine Release, OT_t
(26)

Total Energy Generated, EG_t
(27)

Energy Deficit
(28)

Energy Surplus
(29)

Irrigation Deficit
(30)

Water Supply Deficit
(31)

Closing Balance, S_t
(32)

*** If -ve, then zero.**

APPENDIX - II

DETAILED ALGORITHM FOR RESERVOIR OPERATION

Calculation Steps:

(i) Cols. (1) to (10) are self explanatory

(ii) Col. (11) follows RHS of constraint equation (2)

(ii) Cols. (12) to (15) are self explanatory

(iv) Col. (16) is self explanatory and should follow constraint equations (5) and (6)

(v) Col. (17) is self explanatory

(vi) In Col. (18) the energy demand/dependable flow, Od'_t, is calculated by

$$Od'_t = \left[\begin{array}{l} \text{Energy demand} \\ \text{Or} \\ \text{Dependable flow} \end{array} \right. = \frac{ER_t}{C_f\,(9.8)\,(He_t)\,(e)(h_t)}$$

Where,

ER_t = Energy demand in time t

He_t = EL_t - tail water level

(vii) In Col. (19) release Oe_t is defined as

Oe_t = Or_t If actual water supply release Or'_t can be used for power generation

= Oa_t if actual irrigation release Oa'_t can be used for power generation

= $(Or'_t + Oa'_t)$ if both, Or'_t and Oa'_t can be used for power generation

= 0 if Or'_t and Oa'_t cannot be used for power generation

Then the energy generated at this stage is given by

Energy generated = $C_f\,(9.8)\,(Oe_t)\,(He_t)\,(e)\,(h_t)$

Also, $Oe_t \leq OTmax_t$

Where, $OTmax_t$ = maximum turbine discharge

$$= \frac{H}{C_f(9.8)\ (He_t)\ (e)}$$

Where, H = Power plant capacity

(viii) Col. (20) is self explanatory and should follow constraint equations (5) and (6), Also,

$Oe_t + Oa''_t \leq OTmax_t$

(ix) Co. (21) follows :

Energy generated = $C_f\ (9.8)\ (Oa''_t)\ (He_t)\ (e)$

(x) Col. (22) is self explainatory

(xi) Col. (23) follows RHS of constraint equation (1)

(xii) The reservoir spill Sp_t in Col. (24) is defined as unutilised water which can not be stored over capacity of $Ymax_t$

(xiii) Col. (25) follows constraint equation (3), i.e.,

$O_t = Or'_t + Oa'_t + Oa''_t + Sp_t$

(xiv) Check if Sp_t can also generate energy, i.e., Col. (26) is

$OT_t = Oe_t + Oa''_t + Sp_t$ such that

$OT_t \leq OTmax_t \leq O_t$

Where
OT_t = Total turbine release

(xv) Col. (27) is total energy generated, i.e.,

$EG_t = C_f\ (9.8)\ (OT_t)\ (He_t)\ (e)\ (h_t)$

(xvi) Col. (28) is,

Energy deficit $= ER_t - EG_t$, if $OT_t < Od''_t$

$= 0$,otherwise

(xvii) Col. (29) is,

Energy surplus $= EG_t - ER_t$, if $OT_t > Od''_t$

$= 0$, otherwise

(xviii) Col. (30) is,

Irrigation deficit $= Od_t - Oa'_t$, if $Oa'_t < Od'_t$

$= 0$, otherwise

(xix) Col. (31) is,

Water supply deficit $= Or_t - Or'_t$, if $Or'_t < Or_t$

$= 0$, otherwise

(xx) Col. (32) follows equations (1) through (4)

$S_t = Ymax_t$, if $Sp_t > 0$

$=$ RHS of equation (1), $Sp_t \leq 0$

APPENDIX - III

RESERVOIR OPERATION FOR WATER SUPPLY/IRRIGATION

Reservoir Operation Principle :

Water is a very vital resource on the earth. A water resource project is very costly, and it is not desirable to allow any shortfall in fulfilment of its purpose. Therefore, a better operation policy is to be obtained to use the water in the judicious and economic way. A conventional reservoir operation policy is often used for operation, resulting in reservoir failure during critical flow (low flow) period. On the other hand, the probability of reservoir failure is considerably reduced in the operation with rule curve.

Reservoir Operation with Conventional Rule :

The reservoir will operate under the following basic constraints.

(1) The volume of water released during any period can not exceed the contents of the reservoir at the beginning plus the flow into the reservoir during the period, i.e.,

$$O_t \leq S_{t-1} - Ymin_t + I_t + P_t + I'_t - O'_t - EI_t \quad \text{for all } t \qquad (1)$$

Where,

$$O_t = Oa_t + Sp_t$$

(2) The continuity equation for reservoir is defined as,

$$S_t = S_{t-1} + I_t + P_t + I'_t - O'_t - EI_t - O_t \quad \text{for all } t \qquad (2)$$

(3) The contents of the reservoir at any period can not exceed the capacity of the reservoir, as well as dead storage of the reservoir puts a lower limit on the reservoir storage, such that,

$$Y_d = Ymin_t \leq S_{t-1} \leq Y \quad \text{for all } t \qquad (3)$$

Reservoir Operation with Single Rule Curve :

A Rule Curve Operation with constraints (1) and (2) and a modified (3), 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.

Hence, the constraint (3) is modified as follows :

$$Y_d \leq Ymin_t \leq S_{t-1} \leq Y \qquad \text{for all } t \qquad (3a)$$

Reservoir Behaviour Indices :

(a) Shortage Index (S.I.) : It is the measure of the number and magnitude of annual shortage for irrigation. Lower shortage index indicates more adequately meeting the irrigation requirement.

$$\text{Shortage Index} = \frac{100}{N} \sum_{1}^{N} \left[\frac{\text{Annual Irrigation Shortage}}{\text{Annual Irrigation Target}} \right]^2$$

Where, N = period of analysis in years.

(b) Probability of Failure (P_e) : Probability of failure of a reservoir is the proportion of time units during which the reservoir is empty to the total number of time units used in the analysis.

$P_e = \dfrac{P}{12N}$, where, P = number of time units (months)

during which the reservoir is empty.

(c) Reliability (R_e) : The reliability of a reservoir is defined as $R_e = 1 - P_e$

These definitions enable comparison to be made between different operation policies.

A Case Study

The Kolar river a right bank tributary of river Narmada originates from the Vindhyan range of hills and joins the river Narmada near Village Neelkanth on its right bank. The total length of the river Kolar upto the confluences with Narmada is about 103 kms. and the total catchment area of the river is 1352 km^2.

The project envisages construction of a composite dam with a reservoir capacity of 270 Mm^3 across River Kolar intercepting a catchment area of about 508 km^2. The Kolar project is situated at about 30 kms from origin and is about 2.4 kms. downstream of village Lawakhedi in Sehore district of Madhya Pradesh. The water from the reservoir will be released into the river for irrigation (annual utilisation of 183.6 Mm^3) and will be picked up at about 30 kms downstream of dam where a barrage with regulators for irrigation canals on both the banks is proposed to be construct`ed. The catchment area below the dam upto the pick up weir site is about 251 km^2. Whereas the water for the water supply (annually

56.6 Mm^3) to Bhopal city will be directly drawn from the reservoir, the water requirement for irrigation will be partly met from Kolar reservoir and partly from the concurrent contribution from the catchment area between the dam and the pick up weir site. The observed monthly average river flows are given in Table 3. The index map is shown in Figure 3.

Table 3 Runoff, Evaporation and Water Requirements

Month	Av. runoff+ at project site	Ave. runoff+ below Dam upto Pick up weir	Reservoir evap. in mm	Irrigation requirement as percent of annual demand	Water supply requirement
J	21.26	11.48	280	4.83	4.93
J	69.21	35.25	200	7.34	4.63
A	135.66	73.26	120	0.40	4.63
S	63.90	37.94	120	8.68	4.63
O	12.96	7.02	120	11.98	4.63
N	0.00	0.00	100	17.71	4.63
D	0.00	0.00	80	18.18	4.63
J	0.00	0.00	90	16.38	4.63
F	0.00	0.00	120	11.48	4.63
M	0.00	0.00	190	3.02	4.93
A	0.00	0.00	230	0.00	4.93
M	0.00	0.00	370	0.00	4.93

+ in Mm^3 (million meter cube)

(a) Operation with Conventional Rule :

The annual irrigation and annual water supply targets considered as per the project have been taken for the operation. The results are presented in Table 4. As per the norms the water supply targets and the irrigation targets should be met with 100% and 75% respectively. These norms are not met with the conventional operation, as seen from Table 4, i.e. irrigation 64% and water supply 74% only.

(b) Operation with Single Rule Curve :

The storage provision of 5 Mm^3 as per projects has been kept as the lower limits for storages (rule curve values) which can reach at the end of the months for June, July, August, and September. For the month of May the lower limit has been computed as Dead Storage plus the water supply requirement of June plus evaporation from the reservoir during June. Likewise the lower limit of April will be the lower limit of May plus the water supply requirement of May plus reservoir evaporation during May. Proceeding similarly the lower limits for March, February, January, December, November and October have been computed. They are as below :

Jun	5.00 Mm^3
May	10.93 Mm^3
Apr	17.86 Mm^3
Mar	24.79 Mm^3
Feb	30.92 Mm^3
Jan	36.65 Mm^3
Dec	42.68 Mm^3
Nov	47.91 Mm^3
Oct	54.10 Mm^3

Table - 4 Reservoir Behaviour Studies

Sl. No.	ANIR	Monthly shortage of irrigation and Spills (Nos.)												No. of failures**		Percentage dependability	
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	IRRI	WS	IRRI	WS
		S D	S D	S D	S D	S D	S D	S D	S D	S D	S D	S D	S D				
1.+	183	0 10	0 0	23 0	25 0	8 0	0 1	0 9	0 7	0 8	0 9	0 10	0 13	12	13	64	74
2.*	183	0 8	0 0	23 0	25 0	8 1	0 3	0 7	0 8	0 13	0 14	0 0	0 0	19	1	62	98

+ Conventional Rule, * Single Rule Curve
** Indicates failures out of 50 years

ANIR = Annual Irrigation Requirement, S = Spill, D = Deficit/Shortage, WS = Water Supply, IRRI = Irrigation

In the above computations the maximum reservoir evaporations for June, May, April, March, February, January, December, and November have been considered from trial working table. The rule curve now proposed from June to May is as below :

Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lower limits of storage (Mm^3)	5	5	5	5	54.1	47.91	42.68

Month	Jan	Feb	Mar	Apr	May
Lower limits of storage(Mm^3)	36.65	30.92	24.79	17.86	10.93

The results are given in Table 4. The conventional policy and the rule curve are graphically shown in Figure 4.

The reservoir operation study has suggested that with the rule curve about 98% success in meeting annual water supply target of 56.6 Mm^3 and 62% success in meeting annual irrigation demand of 183 Mm^3 from the reservoir is ensured. A further simulation study has suggested that the restriction of annual irrigation demand to 170 Mm^3 can ensure 76% success in meeting the irrigation demand, with this rule curve.

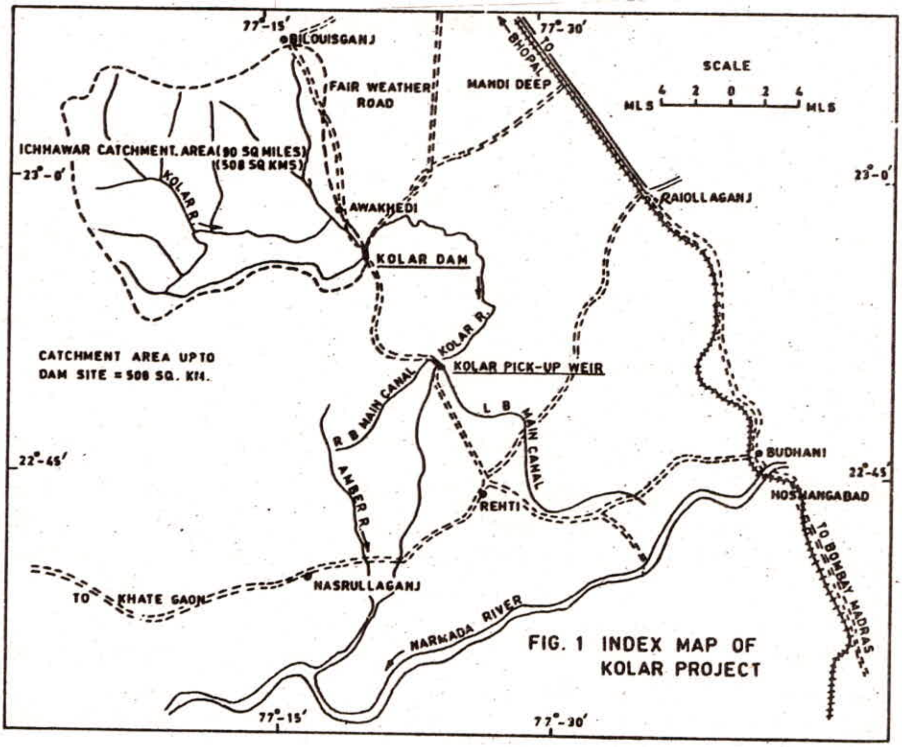

Fig. 3 Index Map of Kolar Project

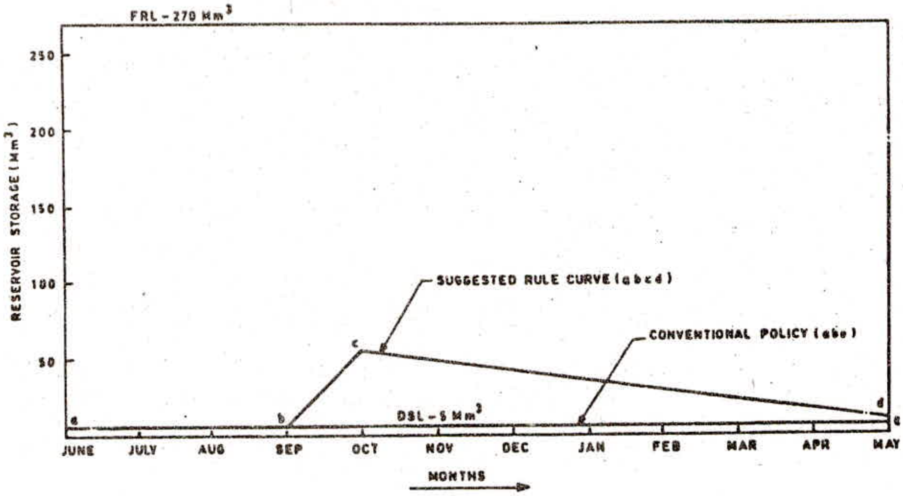

Fig. 4 Rule curve for Kolar Project

References :

Srivastava, D.K. and Valsalan, A.K., 1988. "Conservation of Water in Kolar Project for Bhopal City Water Supply", Second IWRS Symposium on Water Conservation for National Development, Bhopal, Dec. 11-12.

Valasan, A.K., 1985. Modelling of Kolar Irrigation Project for Optimum Water Utilisation, M.E. Dissertation, Deptt. of Hydrology, Univ. of Roorkee, Roorkee.

APPENDIX - IV

RESERVOIR OPERATION FOR HYDROPOWER

Hydropower is one of the major water uses. This forms an important part of a multi-purpose reservoir. Reservoir operation/regulation 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.

Reservoir Operation With Conventional Rule :

With the aid of the constraints (1), (2), and (3) given earlier in the chapter, the simplest operating rule is to supply all the water demand, if available. In this situation, the release is almost independent of reservoir content and season. If there is insufficient water in the reservoir to meet the required releases, the reservoir empties. This simple phenomena is called the conventional rule.

Water Balance of Reservoir :

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

$$S_{12} - S_o = (\Sigma\ I_t) + (\Sigma\ P_t) - (\Sigma\ EI_t) + (\Sigma\ Oa''_t) + (\Sigma\ Sp_t)$$

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 targetted energy
(iii) Regulation for maximum energy

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

(a) Dependable and Targetted Energy Regulations

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

$$\left.\begin{aligned} Oa''_t &= Od''_t \\ OT_t &= Oa''_t \end{aligned}\right] \quad \text{for all t, if there is a reservoir spill.}$$

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

(b) Maximum Energy Regulation

$$OT_t \leq OTmax_t$$

Reservoir Regulation Example :

Table 5 shows operation of a reservoir for the regulation of a run of river hydroplant for maximum energy generation. Table 6 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. A computer programme can be developed using above equations.

O'_t - Release to natural channel (downstream riparian rights) from reservoir in time t

Oa''_t - Reservoir release for hydropower in time t

Od''_t - Energy demand in time t

OT_t - Turbine release in time t

$OTmax_t$ - Maximum turbine capacity in time t

P_t - Precipitation directly upon reservoir in time t

S_{t-1} - Reservoir storage in the beginning of time t

S_t - Reservoir storage at the end of time t

Sp_t - Reservoir spill in time t

t - Any time

Y - Total capacity of reservoir at maximum pool level

Yd - Dead storage of reservoir

Table 5 Run of River Regulation for Maximum Energy Generation

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

Month t	Opening Balance S_{t1}	Inflow I_t	Rain fall P_t	Energy required/dependable Flow Od''_t	Balance (6) = (2)+(3)+(4) -(5)	Mean Storage (7) = $\frac{(2)+(6)}{2.0}$	Water Spread (As_t) in	Evaporation, (El_t) (9) $As_t = Ep_t.k$	Head He_t, in m.	Closing Balance S_t	Spills Sp_t	Energy: Turbine Discharge OT_t	Energy: Generated EG_t in kwhr
1	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	438005
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), $OTmax_t$ = 1.47

Table 6 Reservoir Regulation for Depenable Engrgy

Gross Storage, Y = 1746, (U/s reservoir) Dead Storage, Yd = 0, Live Storage = 1746

Month	Opening Balance S_{t1}	Inflow I_t	Rain fall P_t	Energy required/dependable flow Od''_t	Balance (6) = (2)+(3) +(4)-(5)	Mean Storage (7)= $\frac{(2)+(6)}{2.0}$	Water Spread (As_t) in. hect.	Evaporation, (El_t) $As_t = Ep_t.k$	Head He_t in m.	Closing Balance S_t	Spills Sp_t	Turbine Discharge OT_t	Energy Generated EG_t in kwhr
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Aug	1746	8800	-	210	10336	-	-	-	235	1746	8590	8800	17851x10
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 $\frac{ER_t}{(9.8)\ C_t He_t h_t}$, where ER_t = monthly energy demand, in kwhr

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

$OTmax_t = \frac{H}{9.8\ C_t\ He_t\ .e}$, where H = power plant capacity in kW. $OTmax_t = \frac{100 \times 100}{(9.9 \times 0.003858 \times 235 \times .85)}$ = 13241 hectm.

(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

APPENDIX - V

RESERVOIR OPERATION FOR FLOOD CONTROL

INTRODUCTION

Reservoirs are designed to hold excess flood waters temporarily in storage during the passage of floods and thereby reduce flooding at the affected down stream reach or reaches of the river. One of the essential features of reservoir operation for flood moderation is that storage space earmarked for flood storage is to be held empty throughout the flood season, except during passage of floods when all flood waters will be stored temporarily to prevent down stream flooding. To achieve this and also to prevent unnecessary storage in the flood control space of the reservoir for instance in the early part of a flood, it is important that sufficient discharging capacity at the bottom flood pool levels is available. Further, when flood storage space is occupied maximum possible releases subject to down stream constraints have to be allowed, as far as possible in order that this space can be vacated before the outset of the next flood.

In general, flood potential varies over the year or seasons due to seasonal variations in storm rainfall potential and catchment wetness conditions. Because of this seasonal variation in flood potential the requirements of flood control storage space may also vary seasonally.

Operation of flood control reservoirs can be made more effective if accurate forecasts of inflow are available for areas both above and below dam. Conceptually, if a perfect advanced knowledge can be assumed about the inflows over a time period and the time reservoir will take to fill and empty itself, the flood releases can be so planned as to make the most beneficial use of the available storage space in each and every flood event. Indeed such an ideal operation could even take advantage of depleting the reservoir in the early part of the flood thereby creating an additional space for flood storage, provided that was permissible.

For reasons of economy, multiple use of reservoir storage space is almost invariably restored to by combining flood control with other uses like hydropower and irrigation. In such cases effort is to strike maximum compromise between the conflicting requirements of flood control and consumption by restoring just of as much storage space as possible for both the objectives. Since space requirements for flood control may reduce towards the end of flood season, and since filling of storage for conservation takes place only progressively, some compatibility can always be achieved in that sacrificing too much.

FLOOD CONTROL RESERVOIR OPERATION

Reservoir Operation Questions

There are two basic reservoir operating questions regarding operation of flood reservoir :

1. **Use of flood storage**: Whether flood inflows should be stored to reduce current damage or released to provide additional storage space in case new rains produce even greater flows (i.e., release of flood waters during floods from the flood storage space).

2. **Use of total storage** : Whether storage space should be filled to save water for beneficial use or emptied to contain potential floods (i.e., whether to use flood storage space temporarily for conservation during flood or vise versa).

Reservoir Operation With Zoning or Partitioning

In a multipurpose reservoir when the demands for water are competitive for the same time period, storage volumes in the reservoir must then be allocated to meet these compititive demands. This partitioning process involves both determination of required volumes, and establishing operating rules to specify how the reservoir is to be managed. The elevations of the various zones are used as guides for operation and can vary seasonally (Watershed Resources Management and Environmental Monitoring, 1981).

The following two zones might be considered for flood operation :

1. **Surcharge zone** : The storage above the flood control zone is associated with actual flood damage. The top of the flood control pool is used to maintain the integrity of the reservoir. Reservoir releases are usually at or near their maximum to prevent the dam from collapsing when the storage volume is within this zone.

2. **Flood control zone** : A reserve for storing large inflows during periods of abnormally high runoff. The flood control zone would be evacuated of water, at a time corresponding to the flood season. The reservoir would then be kept at the top of conservation space (bottom of flood control space) to provide sufficient storage to control flooding. Once the pool elevation is in this zone, the reservoir is operated to release the maximum amount of water without causing flooding. Ideally, this would coincide with bankfull conditions down-stream.

Reservoir Release Policy During Passage of Flood

Rules for deciding reservoir releases during the passage of floods keeping in view the release criteria discussed and the consideration of dam safety and where more than one reservoir are involved additional rules for deciding the priorities of releases, between reservoirs are also necessary. Conceptually, there is an optimal operation policy associated with any given system and system inputs and outputs. However, when choice is to be made by taking several alternative designs, it is usually not feasible to search and specify optimal policies for each design. On the other hand in management problems where the system is known, the optimisation for operation policy can be attempted by simulation.

Flood Routing Study of Kangsabati Reservoir

In this the flood routing study of Kangsabati Reservoir (Roy, 1983; Srivastava and Roy, 1993) is presented. The Kangsabati dam is situated on the river Kangsabati in the district of Bankura, West Bengal. The catchment area upto the dam site is 1400 sq. miles, leaving a catchment area of 900 sq. miles downstream. The river is purely a seasonal river originating from the hills of Chhotanagar range in the district of Purulia, West Bengal. The reservoir provides a total flood cushion of about 3.0 million acre ft., between the monsoon flood storage level of 434.0 feet and the maximum flood storage level of 445.0 feet. The design discharge of the spillway is 3.75 million cusecs corresponding to a flood of 1000 years frequency. The dam is provided with 11 numbers of gates with their sill levels fixed at R.L. 408 feet, each bay being 30 feet.

The flood volume for the spillway design flood hydrograph is 14 lacs ac-ft., with the peak inflow of 3.75 lacs cusecs spread over a base period of 10 days. Whereas, the reservoir design flood hydrograph of 100 years frequency has a volume of 9.6 lacs ac-ft., with the peak inflow of 2.68 lacs cusecs spread over a base period of 10 days, Figure 5.

The study has been carried out firstly, to moderate the floods of 100 and 1000 years return periods in order to utilise the minimum flood storage as far as possible and increasing conservation storage with the existing stipulation made for routing for the Kangsabati reservoir and secondly, to minimise the routed outflow as far as possible by the formulation of new flood operation policy, increasing simultaneously conservation storage. Various reservoir release policies during floods for 100 and 1000 years frequency floods are given in Tables 7 and 8 respectively.

The reservoir flood routing was carried out with a routing period of 3 hours. The maximum rise in the water levels in the reservoir and maximum routed outflows are given in Table 9 and 10 for 100 and 1000 years frequency floods respectively.

With the help of the modified stipulation in the flood operation policy it is possible to moderate the peak flood discharge of 1000 years frequency to 2.0 lacs cusecs from 3.75 lacs cusecs.

The reservoir water elevation and the rate of its rise with the time are shown in Figure 6.

Table 7 - Reservoir Release Policy during Flood for 100 years Frequency Flood

Policy No.	Reservoir Water Level, in feet	Release Policy (Outflow), in cusecs
1*	432-434**	Smaller of 50% of Inflow or 40,000
	434-436	Smaller of Inflow or 60,000
	436-440	90,000
	440-445	1,60,000
2	436-438	Smaller of Inflow or 60,000
	438-440	90,000
	440-445	1,60,000
3	438-440	Smaller of Inflow or 90,000
	440-445	1,60,000
4	> 436	Smaller of Inflow or 1,00,000

* Original stipulated reservoir flood operation policy as given in the project.

** In case heavy rainfalls are anticipated start routing from RL 432, otherwise, from RL 434.

Table 8 - Reservoir Release Policy during Flood for 1000 years Frequency Flood

Policy No.	Reservoir Water Level, in feet	Release Policy (Outflow), in cusecs
1*	As per Original Stipulated Policy	As per Original Stipulated Policy
2	436-440	Smaller of Inflow or 1,00,000
	440-445	2,00,000

* Policy No. 1 of Table 7.

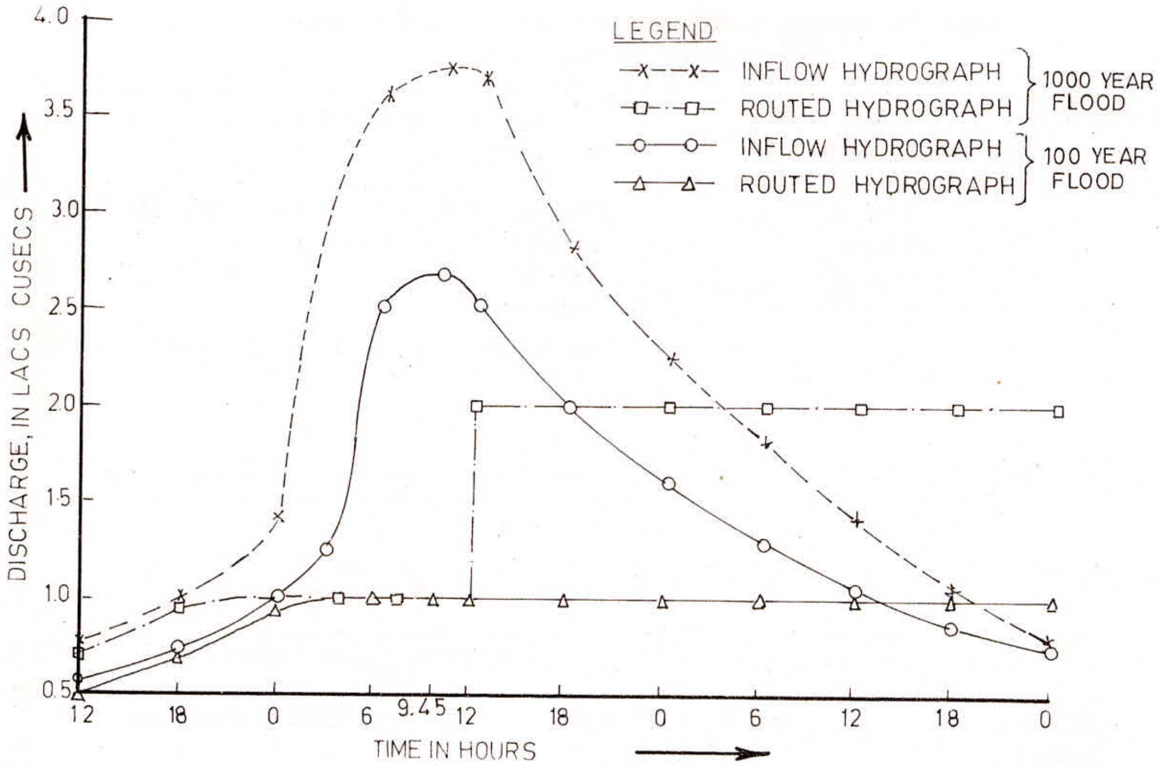
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
DISCHARGE, IN LACS CUSECS
LEGEND
INFLOW HYDROGRAPH
ROUTED HYDROGRAPH
1000 YEAR FLOOD
INFLOW HYDROGRAPH
ROUTED HYDROGRAPH
100 YEAR FLOOD
12
18
0
6
9.45
12
18
0
6
12
18
0
TIME IN HOURS

Fig. 5

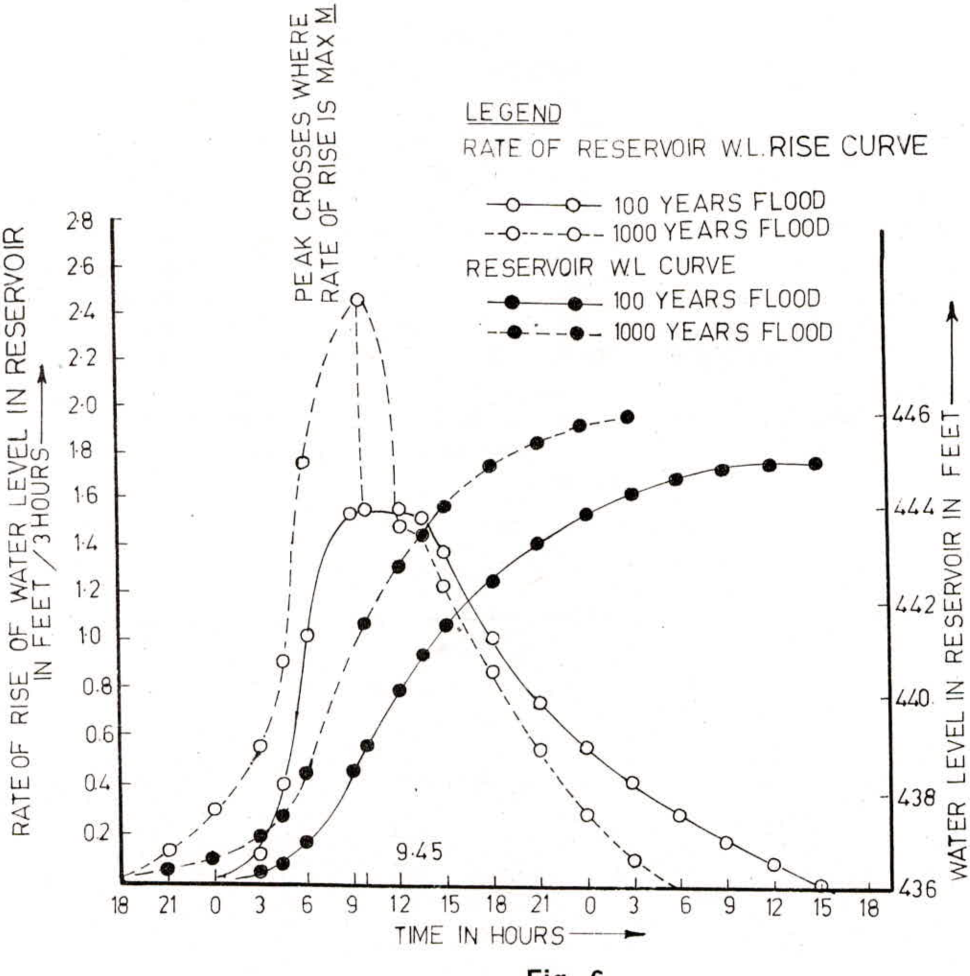
PEAK CROSSES WHERE RATE OF RISE IS MAX M
LEGEND
RATE OF RESERVOIR W.L. RISE CURVE
100 YEARS FLOOD
1000 YEARS FLOOD
RESERVOIR W.L CURVE
100 YEARS FLOOD
1000 YEARS FLOOD
RATE OF RISE OF WATER LEVEL IN RESERVOIR IN FEET/3 HOURS
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
9.45
18 21 0 3 6 9 12 15 18 21 0 3 6 9 12 15 18
TIME IN HOURS
446
444
442
440
438
436
WATER LEVEL IN RESERVOIR IN FEET

Fig. 6

Table 9 - Flood Routing Results for 100 years Frequency Flood

Policy No.	Maximum rise in Water Level in Reservoir, in ft.	Peak Outflow from Reservoir, in lacs cusecs	Reduction in Inflow Peak, in lacs cusecs
1	443.110	1.6	1.08
2	442.665	1.6	1.08
3	443.890	1.6	1.08
4	444.894	1.0	1.68

Table 10 - Flood Routing Results for 1000 years Frequency Flood

Policy No.	Maximum rise in Water Level in Reservoir, in ft.	Peak Outflow from Reservoir, in lacs cusecs	Reduction in Inflow Peak, in lacs cusecs
1	447.111	1.6	2.15
2	445.789	2.0	1.75

Conclusions

1. It has been seen that limiting the outflow to 1.6 lacs cusecs as per original flood operation policy, it is possible to increase the conservation storage to R.L. 438 in case of 100 years frequency flood. Increase in conservation storage results utilisation of flood storage for irrigation.

2. With the revised flood operation policy number 4, Tables 7 and 9, for the 100 year flood, a balance has been reached, i.e., maximum outflow has been further lowered by limiting it to 1.0 lacs cusecs and raising the maximum monsoon storage level to R.L. 436.

3. For 1000 years frequency flood, with the modified flood operation policy number 2. Table 8 and 10, it may also be possible to moderate the flood peak to 2.0 lacs cusecs. This shows a reduction of 45 percent in the inflow flood peak of 3.75 lacs cusecs.

4. The time at which the flood peak has occurred can be known from the point at which the maximum rate of rise of reservoir water elevation has taken place.

5. For the reservoir design flood (100 years frequency) and for the spillway design flood (1000 years frequency), the maximum reservoir routed outflow upto the R.L. 440 is 1.0 lacs cusecs. Beyond this level, the maximum routed outflow has to be increased to 2.0 lacs cusecs for the spillway design flood only.

   This requires proper identification of the type of flood approaching the reservoir, in terms of its frequency well before the full utilisation of the flood storage space is made in the reservoir.

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