REAL TIME RESERVOIR OPERATION (CALIBRATION PHASE): A CASE STUDY

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Abstract

In this work the real time reservoir operation is tackled by LP formulation, which is minimization problem. The objective function is the penalty value, contributed by deviation of reservoir level from the recommended rule curve, flow at d/s flood control point above the non-damaging flow, absolute flow at the d/s flood control point and the rate of increase or decrease of release from reservoir. The constraints of the LP formulation are mass balance of the reservoir, calculation of deviation of reservoir level from the recommended rule curve, flow at d/s flood control point, flow above the non-damaging flow, rate of increase and decrease of release from the reservoir and all other physical constraints of the reservoir. The real time operation is done in two phases, calibration and validation phases. The calibration phase is dealt in this paper, where as validation phase is dealt in the next paper. The parameters of LP formulation are obtained in calibration phase. Three extreme floods from the history of the reservoir are considered during the calibration phase. The LP formulation with different sets of penalties in the objective function is run for these three floods. The performance is evaluated by maximum level achieved by the reservoir, peak flow at Naraj, and duration of operation of flood. The best set of penalties is selected based on this performance.

***Keywords**: Real time reservoir operation, variable rule curve, calibration phase, adaptive*

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1. INTRODUCTION

In developing countries, major river basins are not fully developed to their potential due to scarcity of funds, even if planning for most of them is completed. The objectives of the reservoir system of a basin, considered during planning stage, are tried to be achieved up to maximum possible extent by the constructed reservoirs. But these satisfied objectives are less than the required in the reservoir system. This situation will continue until full development of the river basin is achieved. The operation of this type of reservoirs is quite challenging.

Reservoir operation is one of the major research areas in water resources for last four decades. Many approaches with complex mathematical programs are developed to achieve various objectives of the reservoir. But very few are adopted in actual practice. Three important reasons for this are pointed out by *Simonovic* (1992). These are

1) Reservoir operators are not directly involved during development of the reservoir operation models. The mathematical model developed for the system by academician is not acceptable to the reservoir operators due to the mathematical complexity involved in it.
2) The complex mathematical models are applied to a simplified version of the real system.
3) The operator-academician interaction is negligible due to institutional constraints.

All the above factors are experienced in the case of an existing reservoir at Hirakud, in Mahanadi basin of Odisha, India. Three reservoirs in the basin were originally proposed for full development of the basin (*Patri*, 1993). But only one was constructed in the year 1956 at Hirakud. Till now, there is no proposal for construction of any more reservoirs due to shortage of funds, public protest and above all, for lack of political will-power. Hirakud reservoir was constructed mainly to mitigate floods. As no more reservoirs are constructed till date, the existing reservoir is used now both for flood control and conservative purposes. The average total monsoon inflow into the reservoir, observed in the history, is about six times the live storage of the reservoir. So flood control during high flood is extremely difficult and sometimes is quite impossible. Efforts continue for last four decades to extract maximum benefits from this single reservoir of the basin. It is observed that the operating policy in the form of rule curves for the reservoir was changed for six times from 1958 till to date. These changes are due to the climatic and hydrologic changes in the basin and changes in objectives of the reservoir.

A two-phased model for its operation is developed in the present study to tackle these critical situations. In the first phase operating policy for the reservoir on long-term basis is developed (Baliarsingh, 2000; Nagesh Kumar, 2010). Then the procedure of operating the reservoir on short-term basis for flood control is developed in the second phase. This short-term reservoir operation is reported in two papers of this journal. In this first paper calibration of the short-term reservoir operation model is dealt where as in second paper validation of the model is dealt.

2. LITERATURE REVIEW

Reservoir operation is an important area of research in water resources for more than four decades. Many mathematical models for this purpose are developed in this period. But still researchers are not fully satisfied with it as new problems are coming up continuously with time. The various components, those involved in the operation of a reservoir, are different for different systems.

A review and evaluation of multiobjective programming techniques is presented by *Cohon and Marks* (1975). Dynamic programming applications to water resources are reviewed by *Yakowitz* (1982). An excellent state-of-the-art review of the mathematical models developed for reservoir operation was made by *Yeh* (1985). *Lund and Guzman* (1999) discussed about operating rules for the reservoirs connected in series and parallel.

Yeh and Becker (1982) analyzed California Central Valley Project to guide real time decision making for optimal operation. The purposes of the project are hydropower, aquaculture, to overcome salt-water intrusion in delta area, irrigation, and recreation. The constraint method was used for trade-off among these purposes. They suggested that the information of trade-off should be presented to the decision makers by a series of two dimensional plots instead of tabular presentation.

Dagli and Miles (1980) used the adaptive planning approach for a set of four reservoirs connected serially. Each of the reservoirs was of multipurpose type, having hydroelectric, irrigation, and low flow augmentation on downstream of reservoir as various purposes. As per the adaptive planning approach, the release policy is found out for specified number of periods, but only the release of current period is implemented. Again the model is re-run at the end of current period with new set of forecasted data.

Datta and Burges (1984) explored the sensitivity of various performance criteria of reservoir operation to the conflicting storage and release target and the accuracy of streamflow forecast. The compromise solution depends on uncertain future streamflow and the shape of loss function while trade-off between storage and release deviation from respective targets was found.

The optimization model can be used as simulation tool for real time reservoir system operation. *Ginn and Houck* (1989) discussed a method for calibration of the objective function, used in this optimization model. They have developed the method for quadratic class of model. But, the method can also be used for general non-linear programs with polynomial objective function. They demonstrated the use of the method to simulate operation of the Green River basin hydrosystem in Kentucky.

A model for optimal operating policy of a reservoir for multicrop irrigation was developed by *Vedula and Mujumdar* (1992). Three variables, viz., reservoir storage, inflow to the reservoir, and the soil moisture in irrigated area were treated as state variables and intraseasonal periods smaller than the crop growth duration was treated as stage in the SDP model. The model was applied to Malaprabha reservoir in India.

Vedula and Nagesh kumar (1996) developed an integrated model to derive an optimal operating policy for Malaprabha reservoir of India to irrigate multiple crops. The optimization model was conceptually made up of two phases. The first phase was intraseasonal modeling for allocation within a season and second phase was seasonal modeling for allocation over the seasons in the year.

Raman and Chandramouli (1996) evaluated the operating policy for a reservoir with irrigation and inter-basin transfer facility by DP, SDP, and Standard Operating Policy (SOP). The result, obtained by DP, was used to get relationship of optimum release with initial storage, inflow, and demand by linear regression procedure (DPR) and neural network (DPN). The result obtained by SDP, SOP, DPR and DPN were compared by the performance measuring scale of total square deficit and total spill and DPN was found to be the best method.

Kelman et al. (1989) presented a methodology for optimal design of the flood control volume for a system of eight reservoirs on the Parana river in Brazil. The objective function was to minimize the penalties associated with flood protection, i.e., the total firm energy loss.

The followings findings are observed in the above literature.

1) The characteristics and objectives vary widely from one reservoir system to the other. So, no general algorithm for the system operation exists and solution models are dependent on characteristics of the system, availability of data, specified objective function and constraints.
2) The hydro-meteorological data needed for research and development of project is not available up to a satisfactory level.

The following attempts are made in this research work to operate Hirakud reservoir mainly for flood control.

1) The algorithm developed in this work is generalized in nature. This algorithm can very easily be used with little modification for any other project.
2) Satisfactory hydro-meteorological data of the Hirakud reservoir is not available. An unique procedure is adopted for real time operation of this reservoir utilizing these data with modification.

3. DESCRIPTION OF THE STUDY AREA-HIRAKUD MULTIPURPOSE PROJECT SYSTEM

The project under the present study, Hirakud single reservoir system is situated in Mahanadi basin. The Mahanadi basin lies mostly in Madhya Pradesh and Orissa States. It is bounded on the north by Central India Hills, on the south and east by Eastern Ghats and on west by the Maikela range, the south east part of Deccan Plateau. The basin is situated between 80^0 30' and 86^0 50' East longitude and 19^0 20' and 23^0 35' North latitude (Fig. 1). It is roughly circular in shape with a diameter of about 400 Km. and an exit passage of 160 Km. length and 60 Km. breadth. Area of this basin is 1,41,600 sq. Kms. and is broadly divisible into three distinct zones, the upper plateau, the central hill part flanked by Eastern Ghats, and the delta area. Hirakud dam across Mahanadi river is located in the second zone.

Mahanadi river rises from Raipur district of Madhya Pradesh at an elevation of 442 m above mean sea level. The total length of this east flowing river from its origin to its outfall into the Bay of Bengal is 851 Km., of which 357 Km. lie in Madhya Pradesh and remaining 494 Km. in Orissa. After a run of 450 Km. from its starting point, the river reaches Sambalpur district of Orissa, where the Hirakud dam is built across the main river. Below the dam, the river gets water mainly from two sub-basins, Ong and Tel, in addition to free catchment along the river. The river flow up to Naraj, the head of delta. The catchment area up to Naraj is 1,32,200 sq. Kms.. On the d/s of Naraj, the river divides into several branches, namely, Birupa, Chitrotpala, Devi, Kushabhadra, Bhargabi, Daya etc. and runs 80 Km. before discharging into Bay of Bengal.

The multipurpose Hirakud reservoir is utilized mainly for three purposes, flood control, irrigation, and hydropower production. There is expectation from Hirakud reservoir to control flood at coastal delta area by limiting the flow at Naraj within 25.5 thousand cumecs. There are three head regulators, which can draw 128.8 cumecs from the reservoir for irrigation purpose. Areas of 0.16 and 0.11 million hectares are irrigable under the reservoir during Kharif and Rabi seasons respectively. The total installed hydropower capacity of the project is 307.5 MW, out of which 235.5 MW can be produced from seven units of Hirakud hydropower station, and 72 MW can be produced from three units of Chipilima hydropower station, located further d/s of Hirakud dam. The water, used for power generation at Hirakud, flows from Hirakud hydropower station to Chipilima hydropower station through a power channel of 22.4 Km. long. After generating power at Chipilima, water flows again into the river. The schematic diagram of Hirakud project is shown in Fig. 2.

The purposes of this reservoir are flood control, irrigation, and power generation. The first preferred objective is to control flood for the coastal deltaic region of Odisha. This reservoir is situated 400 Km. upstream of confluence of Mahanadi river with the Bay of Bengal (Figs. 1 and 2). There is no other flood controlling structure downstream of Hirakud reservoir. During monsoon season, the coastal delta part, between Naraj and Bay of Bengal, is severely affected by floods. This flood prone area gets water from the Hirakud reservoir and from rainfall in the downstream catchment. Naraj is situated at the head of the delta area, where the flow of Mahanadi river is measured. The flow of Mahanadi river at Naraj is used as the indicator of occurrence of flood in the coastal delta area by Hirakud authority. As Hirakud reservoir is on the upstream side of delta area in the basin, it plays an important role in alleviating the severity of the flood for this area. This is done by regulating release from the reservoir.

4. PROCEDURE FOR OPERATION OF HIRAKUD RESERVOIR

In general the reservoir is operated by following the rule curve meant for that reservoir. At present Hirakud reservoir is also operated by its rule curve. Rule curve for the reservoir is the water level in the reservoir, which should be attained at various time instant. A variable rule curve, i.e. rule curves for different situations, like flood, normal, and drought years have been developed and proposed for Hirakud reservoir by the same author (Baliarsingh, 2000; Nagesh Kumar, 2010). These can be taken as guidelines during actual reservoir operation. This does not mean that the reservoir level will stick to the rule curve at each and every time instant, but it will be as close to it as possible. If inflow into the reservoir is either less or more than the expected amount, the reservoir level deviates from rule curve and again comes back, when favourable situation returns. There should be some guidelines for the reservoir level to deviate from the rule curve.

The reservoir operation is the decision of release from the reservoir at various time periods. Real time reservoir operation is one where the forecasted data, required for taking decision of release for current period, is obtained depending on the observed data. Real time reservoir operation on short-term basis (decision of releases to be taken at smaller time intervals) is required during flood to control the flood efficiently. In this study, the modality of real time operation for Hirakud reservoir on short-term basis is evolved. Adaptive planning (Dagli and Miles, 1980) is followed during the operation here. The process of adaptive planning is as follow. The release for certain future fixed periods, for which necessary forecasted data is available, are determined at the time of taking decision. But the release for the current period only is implemented. This process is done iteratively during each period of operating horizon to obtain release decisions.

5. METHODOLOGY OF REAL TIME RESERVOIR OPERATION

Hirakud reservoir is a multipurpose single reservoir system. The main purpose is flood control. Irrigation and hydropower are the other two purposes. The reservoir controls flood in coastal delta region by controlling the flow at Naraj for non-damaging flow, which is 25.5 thousand cumecs. The total release from the reservoir is the combination of release for power and spill. The release for power is to be met from the total release. If the total released quantity is less than the turbine capacity, then all the released water will be used for hydropower production. If total release is more than the turbine capacity, the excess water after meeting the full turbine capacity is taken as spill.

Ultimately, the release used for power production joins the main river on d/s of reservoir. So the power generation is not considered for maximization, but it is produced as per the availability of release quantity, which is required for flood control. The release decision is taken by the following LP formulation. The objective is to minimize the aggregate of various factors, such as, (i) the deviation of reservoir storage from recommended storage given by rule curve, (ii) deviation of flow at Naraj above the non-damaging flow, (iii) flow at Naraj, when it is less than non-damaging flow, and (iv) rate of change of release from reservoir. Some penalties are assigned to each of these factors as per their importance. These penalties are arrived at by trial and error during calibration phase and are validated during validation phase.

5.1 LP Formulation

The LP formulation is used in both calibration and validation phases for operation intervals of 24 hours, 12 hours and 6 hours. For illustration, the formulation is discussed for the operation interval of 24 hours. The LP formulation is as follows.

Minimize

$$Z = \sum_{t=1}^{L} [P_{LS}\ LS_t + P_{US}\ US_t + P_{QI}\ QI_t + P_{QD}\ QD_t + P_{ROAI}\ ROAI_t + P_{ROAD}\ ROAD_t + P_{ROEI}\ ROEI_t + P_{ROED}\ ROED_t]$$

subject to (1)

$$S_2 + CF * RPS_2/2 = CF\ [I_1 + I_2]/2 - CF\ [IR_1 + IR_2]/2 - CF * RPS_1/2 + S_1 \qquad (2)$$

$$S_t + CF\ [RPS_{t-1} + RPS_t]/2 - S_{t-1} = CF\ [I_{t-1} + I_t]/2 - CF\ [IR_{t-1} + IR_t]/2 \qquad t = 3,4,....,L \qquad (3)$$

$$S_t - US_t + LS_t = RCS_t \qquad t = 2,3....,L \qquad (4)$$

$$QH_2 - C_1\ RPS_2 = C_0\ RPS_1 + C_2\ QH_1 \qquad (5)$$

$$Q_2 = QH_2 + DC_2 \qquad (6)$$

$$QH_t - C_0\ RPS_{t-1} - C_1\ RPS_t - C_2\ QH_{t-1} = 0 \qquad t = 3, 4, ...L \qquad (7)$$

$$Q_t = QH_t + DC_t \qquad t = 3, 4, ...L \qquad (8)$$

$$Q_t - QI_t - QD_t = 0 \qquad t = 2, 3, ...,L \qquad (9)$$

$$RPS_2 - [ROAI_1 + ROEI_1] + [ROAD_1 + ROED_1] = RPS_1 \qquad (10)$$

$$RPS_t - [ROAI_{t-1} + ROEI_{t-1}] + [ROAD_{t-1} + ROED_{t-1}] - RPS_{t-1} = 0 \qquad t = 3, 4....L \qquad (11)$$

$$RPSMIN \le RPS_t \le RPSMAX \qquad t = 2,3, ...,L \qquad (12)$$

$$QD_t \le NDF \qquad t = 2,3, ...,L \qquad (13)$$

$$ROAI_t \le ROAIMAX;\ ROAD_t \le ROADMAX \qquad t = 1,2, ……,L-1 \qquad (14)$$

$$S_{DSL} \le S_t \le S_{FRL} \qquad t = 2,3, ……,L \qquad (15)$$

Non-negative constraints on US_t, LS_t, QI_t, QD_t, $ROAI_t$, $ROAD_t$, $ROEI_t$, *and* $ROED_t$.

$t = 2,3, ……,L$ (16)

Where,
Z is the objective function.
LS_t is the deviation of reservoir storage below the recommended rule curve storage at beginning of time period *t*.
US_t is the deviation of reservoir storage above the recommended rule curve storage at beginning of time period *t*.

QI_t is the difference between flow at Naraj and non-damaging flow at beginning of time period *t*, when the flow is more than non-damaging flow,.
QD_t is the flow at Naraj at beginning of time period *t*, when the flow is less than or equal to non-damaging flow.
$ROAI_t$ is the increase of release from reservoir (summation of release for power and spill) within acceptable safe limit during time period *t*.
$ROAD_t$ is the decrease of release from reservoir within acceptable safe limit during time period *t*.
$ROEI_t$ is the increase of release from reservoir beyond acceptable safe limit during time period *t*.
$ROED_t$ is the decrease of release from reservoir beyond acceptable safe limit during time period *t*.
P_{LS}, P_{US}, P_{QI}, P_{QD} are the relative penalties for unit change of *LS*, *US*, *QI*, *QD* respectively.
P_{ROEI}, P_{ROED}, P_{ROAI}, P_{ROAD} are the relative penalties for unit change of *ROEI, ROED, ROAI, ROAD* respectively.
S_t is the reservoir storage volume at beginning of time period *t*.
CF is the conversion factor to convert from rate to volume of any variable.
RPS_t is the summation of release from reservoir for power and spill at beginning of time period *t*.
I_t is inflow into the reservoir at beginning of time period *t*.
IR_t is the release from reservoir for irrigation at beginning of time period *t*.
RCS_t is the recommended rule curve storage at beginning of time period *t*.
Q_t is the flow at Naraj at beginning of time period *t*.
DC_t is d/s catchment contribution at beginning of time period *t*.
QH_t is the routed quantity of release from Hirakud reservoir at Naraj at beginning of time period *t*.
RPS_t is the release from Hirakud reservoir for power and spill at beginning of time period *t*.
Q_t is the flow at Naraj at beginning of time period *t*.
DC_t is the d/s catchment contribution at beginning of time period *t*.
C_0, C_1, C_2 are coefficients of conventional Muskingum equation.
RPSMIN is the minimum required release from reservoir for power and spill.
RPSMAX is the maximum release capacity from reservoir for power and spill.
ROAIMAX is the safe limit of increase of release from reservoir during a specific time period.
ROADMAX is the safe limit of decrease of release from reservoir during a specific time period.
S_{DSL} is the reservoir storage at dead storage level.
S_{FRL} is the reservoir storage at full reservoir level.
t is the time period.
L is the operating horizon for each iteration of the LP model.

Equations-1 to equation-16 are the multi-objective LP formulation, proposed for operation of Hirakud reservoir on real time basis. *Q* is the flow at Naraj, which is divided into two components *QI* and *QD*. If the flow at Naraj *(Q)* is less than the non-damaging flow, *QD* will be equal to *Q* and *QI* will be zero. If the flow at Naraj *(Q)* is more than non-damaging flow, *QD* will be equal to non-damaging flow and *QI* will be the difference between *Q* and non-damaging flow. *CF* is the conversion factor to find the volume in terms of TMCM from the rate in terms of thousand cumecs. In case of 24 hours operation, $CF = 10^3 * 24 *3600 / 10^9 = 0.0864$. *RPSMIN* is the minimum limit of release from reservoir corresponding to riparian rights. *RPSMAX* is the maximum limit of release from reservoir corresponding to the combination of release capacity through spillway, sluice and powerhouse. *ROAIMAX* and *ROADMAX* are the maximum allowable increase and decrease of release from reservoir respectively within the operating period from safety consideration. These values are 14.169 thousand cumecs per day, specified for Hirakud reservoir. So, these values are considered as 14.169 thousand cumecs in the case of 24 hours operating interval.

The objective function value (equation-1) is the contribution of penalties from *LS, US, QI, QD, ROAI, ROAD, ROEI*, and *ROED* for *L* periods. Equations-2 and equation-3 are the mass balances of reservoir for each time period. *US* and *LS* are calculated from equation-4. Equations-5 to equation-8 are the equations of Muskingum flood routing model to calculate flow rate at Naraj from the known value of release from Hirakud reservoir and d/s catchment contribution rate. *QI* and *QD* are calculated from equation-9. *ROAI, ROEI, ROAD* and *ROED* are calculated from equations-10 and equation-11. Equations-12 to equation-15 show the limits for *RPS*, *QD, ROAI, ROAD*, and *S*.

The real time operation of the Hirakud reservoir is made in this study as per adaptive planning, where the LP formulation is used in iterative manner. The inflow into the reservoir and d/s catchment contribution are forecasted for *L* time steps ahead of t^{th} time step for the decision of release for these *L* time steps. These two forecasted data sets and the recommended rule curve for *L* time steps ahead of *t* are the input data for the above LP model. This LP model is run and the release for *L* time steps are obtained, but only the release of t^{th} time step is implemented. For the decision of $(t+1)^{th}$ time step, again the LP model is run for *L* time steps ahead of $(t+1)^{th}$ time step. This procedure is done iteratively till the operation completes for the whole operating horizon.

Various sets of relative penalty are tried for *QD, US, ROAI, ROAD, QI, LS, ROEI, ROED* in equation-1. For example, the relative value is considered in the ratio of $P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI} : P_{LS} : P_{ROEI} : P_{ROED}$ :: 1 : 3 : 1 : 2 : 8 : 8 : 8 : 8. The penalties for *QI, LS, ROEI* and *ROED* are kept same and sufficiently more than others in all trial penalty sets to avoid any non-zero value for these variables to the extent possible. By this process, the minimization of flow rate at Naraj above the non-damaging flow (*QI*), reservoir level less than the recommended rule curve storage (*LS*), increase and decrease of release from reservoir beyond the allowable safe limits (*ROEI* and *ROED* respectively) are given the high priorities. As the penalties for *QI, LS, ROEI,* and *ROED* are kept same in each trial penalty set throughout this study, the ratio of $P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI} : P_{LS} : P_{ROEI} : P_{ROED}$ :: 1 : 3 : 1 : 2 : 8 : 8 : 8 : 8 is henceforth expressed as $P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI}, P_{LS}, P_{ROEI}, P_{ROED}$ :: 1 : 3 : 1 : 2 : 8.

In this study, the data of inflow into the reservoir and d/s catchment contribution are used for obtaining the operating policy of the Hirakud reservoir. The measurement of inflow into the reservoir was started from 1958 and the d/s catchment contribution was started only from 1972. It is decided to use the data from 1958 itself as some of the most severe floods have occurred during the period 1958 to 1971. The d/s catchment contribution is calculated by subtracting routed outflow of reservoir from flow at Naraj. In this process, the calculated d/s catchment contribution also includes the lateral flow of the Hirakud-Naraj reach. A suitable set of penalties for LP formulation is found by calibrating three severe floods of the period 1958-1995 in the calibration phase. This operating policy (LP formulation) with the suitable penalty set, obtained in calibration phase, is validated in the validation phase.

5.2 Calibration Phase

The penalties of various components in objective function (equation-1) of LP formulation are arrived at in this calibration phase. Flood control is the first preferred purpose during monsoon season. So severe floods from the year 1958 to 1995 are considered for calibration, as the measurement of inflow into the reservoir (once in a day) was started from 1958. The measurement of flow rate at shorter interval for the earlier years are not available, but only the peaks during all the floods of 1958-1995 are available, which are shown in Table-1. The flood hydrographs are generated by assuming that the severe floods have same shape as the probable maximum flood for Hirakud reservoir, as recommended by Hirakud authority (*Patri*, 1993). The inflows into the reservoir corresponding to a flood hydrograph are made to start from the second day of 10 days block period and the corresponding d/s contribution hydrographs are made to start from first day of that block period to take the lag time into the account. The severity of floods is measured here in terms of the peak inflow into the reservoir during the flood. Floods are first arranged in nine block periods (10 days) of the monsoon (31^{st} day of a month is put in the 3^{rd} block of that month). It is assumed that the flood has occurred in a particular block period, if its peak has occurred during that period. The peaks of inflow hydrograph into the reservoir are arranged in these block periods and is shown in table-2. The most severe and second most severe floods are arranged block period wise and are shown in Table-3. These flood data are obtained from Table-1, where the data for all the sixty-eight floods from 1958 to 1995 are shown. In Table-3, duration of flood, peak inflow into the reservoir, and peak calculated d/s catchment contribution are shown. The peak inflows into the reservoir of the most severe flood in first and eighth block periods are 43.2 and 37.7 thousand cumecs. The peak inflows into the reservoir in the other block periods are less than these two peak values. The recommended variable rule curve for flood situation (Fig-3) during the first block period is less and is very close to the dead storage level and the rule curve storage during eighth block period is more and is very close to the full reservoir level. If these two floods can be handled by following the LP formulation during actual operation, then the floods for the other block periods can be handled by the same process. In the second most severe floods, the peak d/s catchment contribution for the flood during eighth block period is 24.9 thousand cumecs. The non-damaging flow at Naraj is 25.5 thousand cumecs. From the angle of d/s catchment contribution, this flood is also severe like the previous two floods. So, these three floods are chosen for calibration to find out the set of penalties for the different components of LP formulation. The inflow into the reservoir and d/s catchment contribution peak of the second most severe flood in the sixth block period are 26.9 and 44.9 thousand cumecs. There is no control over d/s catchment contribution in Hirakud reservoir system. The reservoir operation is same for all the floods, where d/s catchment contribution is more than 25.5 thousand cumecs. There should be no release from reservoir at this situation, considering overflowing of reservoir. The recommended variable rule curve during sixth block period is less than that of eighth block period. Considering the variable rule curve, second most severe flood in eighth block period is more severe than the second most severe flood of sixth block period. However, this second most severe flood of sixth block period is tested in validation phase. The inflow into the reservoir and d/s catchment contribution of most severe flood in ninth block period are 16.9 and 7.1 thousand cumecs. The summation of these two peaks is 24 thousand cumecs, which is less than the non-damaging flow at Naraj. This flood can be tackled, even when the reservoir is at its full capacity, with proper reservoir operation. As such, the recommended rule curve in ninth block period is not at full reservoir level. So this flood is not considered as serious event for calibration. To conclude, most severe floods during first and eighth block periods and second most sever flood during eighth block period are considered for calibration phase and are named as flood numbers 1, 2, and 3 respectively.

The occurrence of calibration flood numbers 1, 2, and 3 was in the year of 1961, 1980 and 1959 respectively. As already mentioned, the measurement of d/s catchment contribution on daily basis was started from 1972. The data for individual inflow into the reservoir and d/s catchment contribution are required to calculate flow at Naraj by Muskingum equation. The value of x and K are 0.2 and 36 hours respectively as recommended by Hirakud. So for daily operation, where Δt = 24 hours, the Muskingum parameters are calculated as per the equations given by Muskingum (Subramanya,2008) and found to be C_0 = 0.471, C_1 = 0.117 and C_2 = 0.412.

6. RESULTS AND DISCUSSION OF CALIBRATION PHASE

The relative penalties for various components of objective function in LP formulation are determined in the calibration phase. The LP formulation for calibration phase is given by equations-1 to equation-16. Three floods, viz., calibration flood numbers 1, 2, and 3 are used here for calibration.

The penalty for the deviation of reservoir storage above the recommended rule curve storage, (P_{US}), was chosen as 3, 4, and 5 during trial. Lower the penalty of *US*, higher will be the value of *US* during LP solution. The reservoir storage space between recommended rule curve storage and actual reservoir storage above recommended rule curve storage is utilized for storing the flood volume. The value for P_{ROAD} is tried with 1 and 2 while P_{ROAI} is tried with only 1. The value of 1 for both P_{ROAI} and P_{ROAD} means, same rate of change of release during both ascending and descending phase of inflow hydrograph. The penalty of 2 for P_{ROAD} and 1 for P_{ROAI} implies the rate of decrease of release during recession of flood is less than the rate of increase of release during rising of flood.

The performance of the reservoir operation is evaluated in two ways; 1) capability of controlling the flood, and 2) capability of filling the reservoir at the end of monsoon season. The floods that can be controlled by reservoir are considered during development of rule curve. The difficulties will be less for controlling the flood, if the reservoir level is followed close to the recommended rule curve. The reservoir filling at the end of monsoon season can be achieved by not allowing the reservoir level to fall below the recommended rule curve. Higher the penalty, lower will be the value of corresponding factor of objective function in LP formulation. Hence P_{LS} is always kept at 8. The flow rate at Naraj above non-damaging flow is important for flood control purpose. But it cannot be avoided in the situation, when either the d/s catchment contribution itself is more than non-damaging flow or a fresh flood comes, when the reservoir is full. Release has to be made for preventing overtopping of the reservoir in the second case. So P_{QI} is also taken as 8. The allowable rate of change of release from reservoir is considered as 14.169 thousand cumecs per day, as recommended by Cental Water Commission (*Patri*, 1993). The rate of change of release beyond this value is treated to be unsafe for earthen portion of the dam from stability point of view. So P_{ROEI} and P_{ROED} are taken as 8 always. As such, 8 is the lowest value for all these four parameters beyond which the performance does not change.

The results of calibration phase for the three calibration floods for various combinations of penalties are shown in Table-4. The performance of various sets of penalties is evaluated by maximum reservoir storage achieved during flood, peak flow rate at Naraj, and duration of flood control operation. During incoming of flood, the reservoir level peaks up at the beginning and then reduces at the end of flood. The recommended release by LP formulation from the reservoir also increases at the beginning and then reduces towards the end. The duration of flood control operation is indicated by the reservoir level and release, which are recommended by LP solution. At the end of flood control operation, release will be close to inflow into the reservoir and reservoir level begins to increase as per the rule curve.

It is observed from the results that the performance for the relative penalty of 3 and 4 for P_{US} is more or less same irrespective of penalties for other factors. Penalty 3 is more preferred than 4 for the fluctuation of reservoir level. More fluctuation under penalty 3 will facilitate the reservoir to fill up at the end of monsoon season. So the penalty of 3 and 5 are considered for comparison.

The duration of flood control operation for calibration flood numbers 2 and 3 is quite less than that of calibration flood number 1. The recommended rule curve during calibration flood number 1 is close to the dead storage level, as this flood occurred during first block period. The rule curve for calibration flood numbers 2 and 3 is much higher than dead storage level. In all the three floods, the reservoir storage has gone up to full reservoir level, i.e., 7.197 TMCM, for storing the flood. So operation took longer period to come back from full reservoir level to the recommended rule curve in case of flood number 1 than that of the other two.

Invariably, the duration of operation is quite long, where the value for P_{ROAD} is chosen as 2. As the calibrated floods are generated as per the shape of probable maximum flood, all the three calibrated floods have considerable amount of inflow up to first six days. Even if the base period of probable maximum flood hydrograph is nine days, the flow reduced to negligible quantity from seventh day onwards. The flow rate on seventh, eighth, and ninth days are 5.2, 3.5, and 1.75 percentage of peak respectively. The duration of flood control is two to nine days more than duration of actual flood depending on the severity of flood and penalty set. The flood duration period should be as little as possible, so that reservoir can be again ready for any consecutive flood. Considering this factor, the value of P_{ROAD} is chosen as 1.

Comparison of trial values for P_{US} of 3 and 5 and P_{ROAD} of 1 is made. It is seen, that with P_{US} as 5, the reservoir has never reached the full reservoir level, but with P_{US} as 3, reservoir reached the full reservoir level for all the three calibration floods. As the full reservoir is used during the floods, value of 3 for P_{US} is preferred. This facilitates the reservoir to be at a higher level after due consideration for non-damaging flow at Naraj.

7. CONCLUSIONS

The flow rate at Naraj is less than 25.5 thousand cumecs except for third flood, where P_{US} is considered as 5. In the third flood, the flow at Naraj is more than 25.5 thousand cumecs at the cost of reservoir level not achieving full reservoir level, which is not acceptable in flood operation. Considering these factors, the trial penalty sets with P_{US} as 5 are avoided. So finally from above discussion and analysis, the relative penalty ratio of $P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI}$, P_{LS}, P_{ROEI}, P_{ROED} :: 1 : 3 : 1 : 1 : 8 is selected for further use. The performance of this set of relative penalty is tested in the validation phase, which is described in the next paper.

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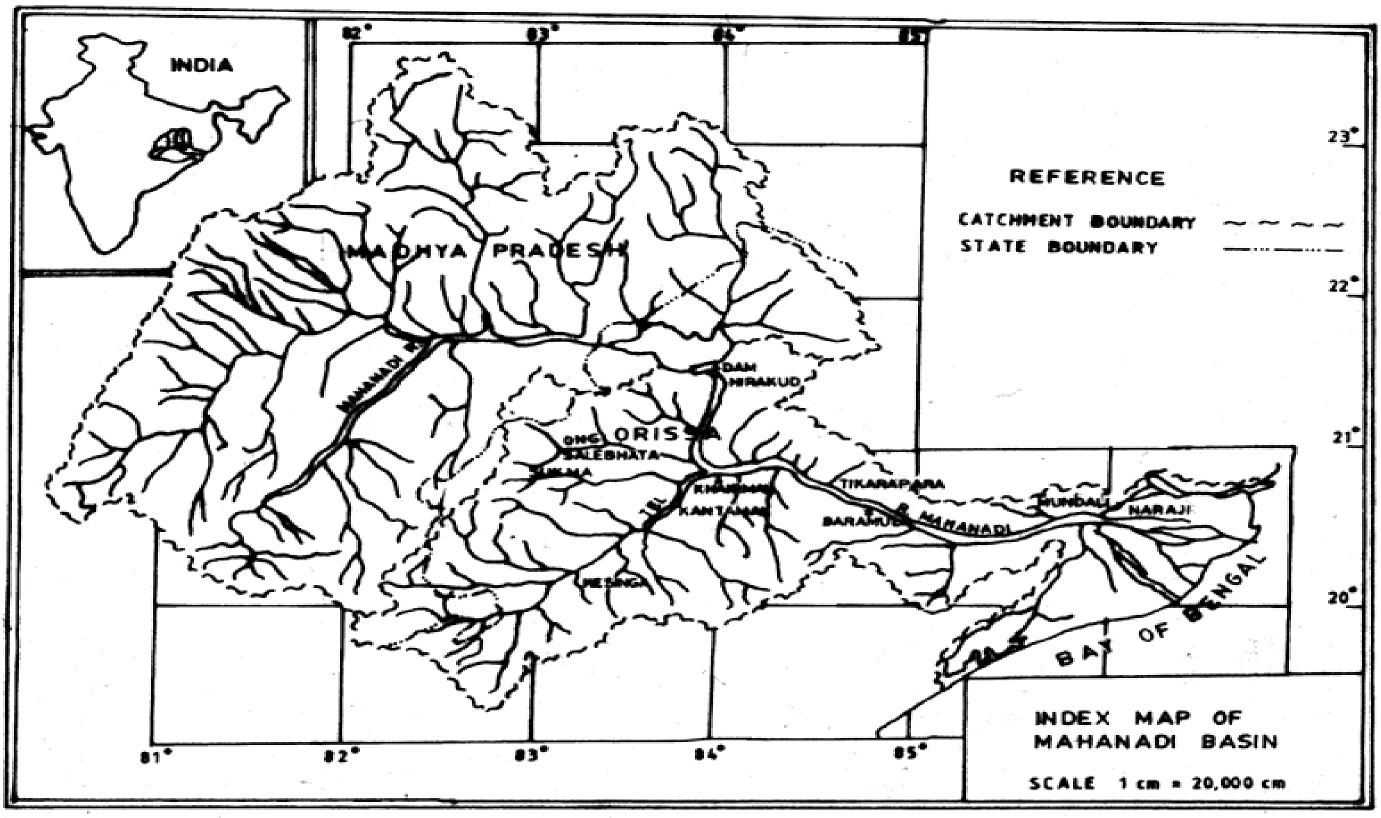

Fig 1: Index map of mahanadi basin

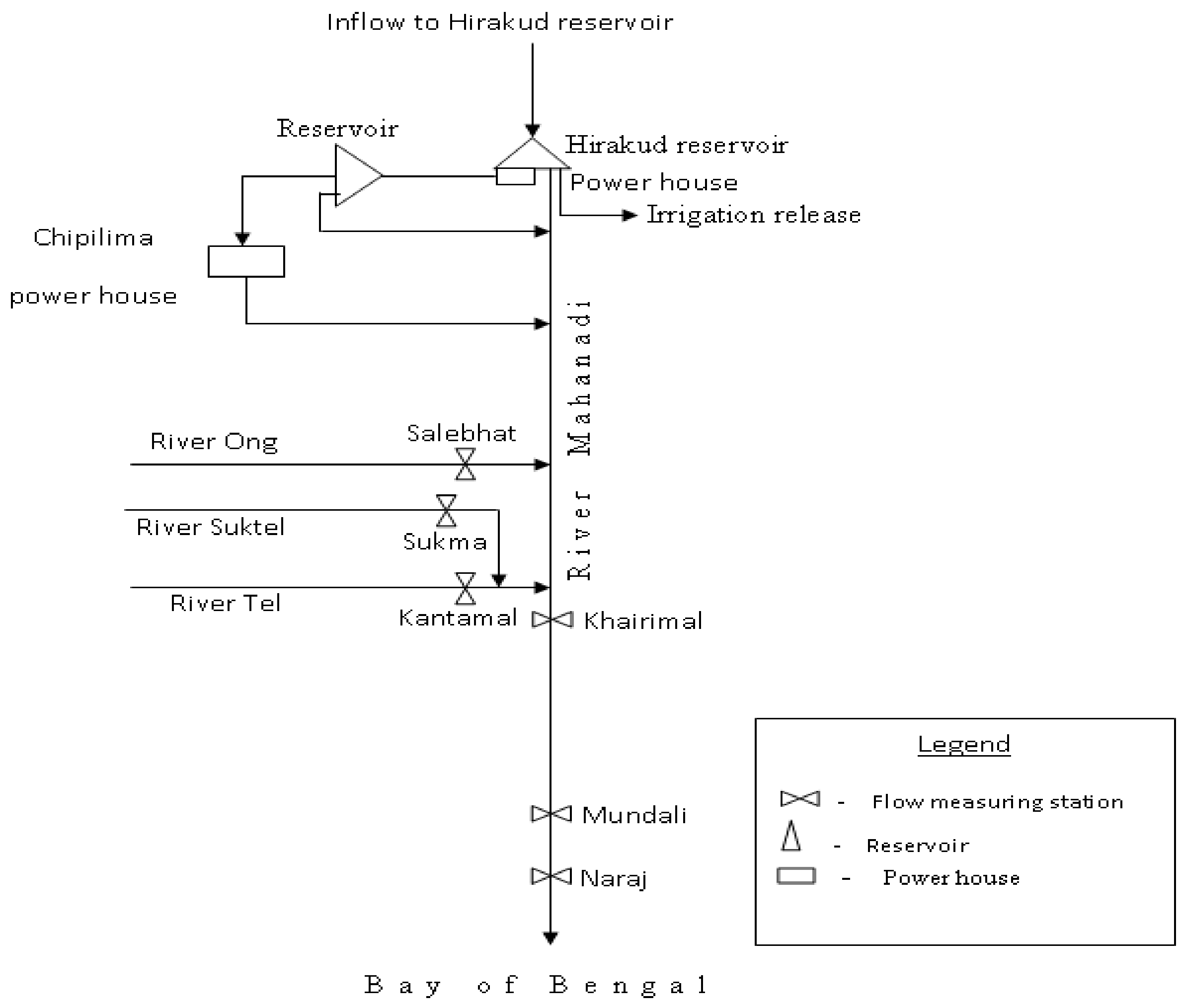

Fig. 2: Schematic Diagram of Hirakud Project

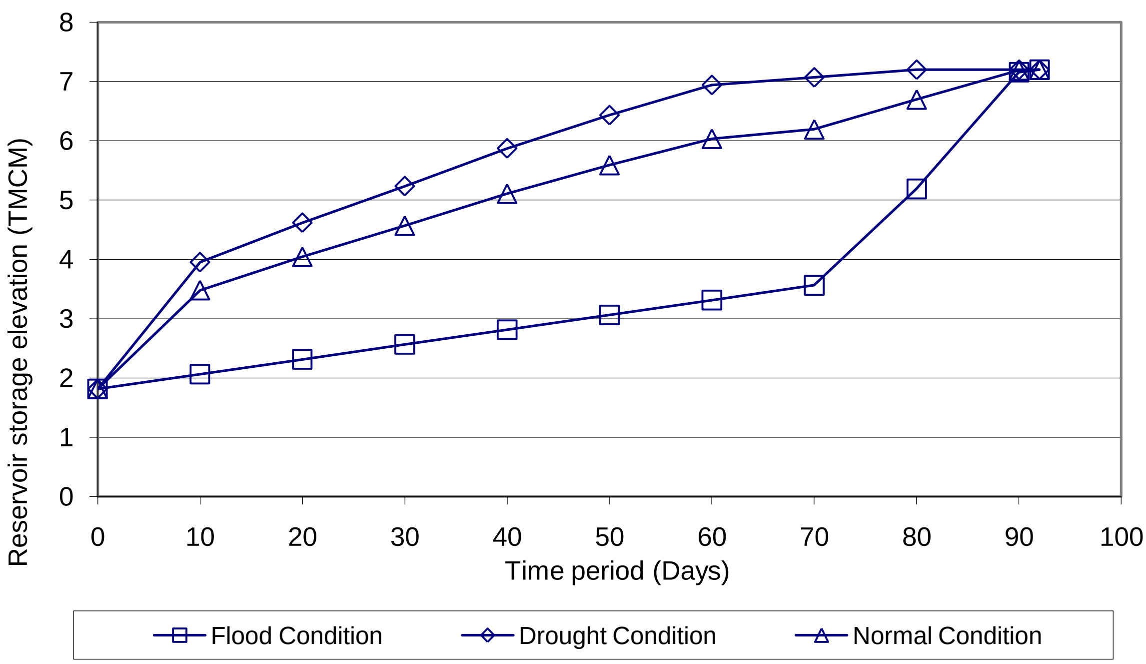

Fig. 3: Variable Rule Curve proposed for Hirakud Reservoir by Baliarsingh (Baliarsingh,2000; Nagesh Kumar, 2010)

Table 1: Historical Floods and Calculation of d/s Catchment Contribution

Sl. No.	Year	Duration of flood	Peak inflow into reservoir		Peak outflow from reservoir	Routed reservoir outflow	Flood peak at Naraj		Peak d/s contribution
			Date	Peak			Date	Peak	
				Thousand Cumec	Thousand Cumec	Thousand Cumec		Thousand Cumec	Thousand Cumec
1	*2*	*3*	*4*	*5*	*6*	*7 = 6**0.74	*8*	*9*	*10 = 9-7*
1	1958	10/7 - 22/7	17-7	23.83	18.62	13.78	19-7	34.01	20.23
2	1959	29/7 - 07/8	05-8	27.49	22.02	16.29	07-8	21.68	05.38
3		10/9 - 18/9	14-9	24.43	14.34	10.61	14-9	35.56	24.95
4	1960	15/8 - 19/8	17-8	23.46	08.98	06.65	19-8	09.63	02.99
5	1961	04/7 - 13/7	10-7	43.22	30.92	22.88	11-7	36.41	13.54
6		16/7 - 26/7	17-7	23.12	16.89	12.50	18-7	32.65	20.15
7		23/8 - 27/8	26-8	15.73	11.25	08.33	25-8	21.71	13.38
8		01/9 - 11/9	08-9	25.79	11.53	08.53	08-9	33.10	24.56
9		14/9 - 17/9	16-9	19.69	17.63	13.04	16-9	36.98	23.94
10	1962	03/8 - 06/8	04-8	07.88	06.15	04.55	05-8	21.40	16.84
11	1963	10/8 - 13/8	11-8	18.42	15.53	11.49	12-8	23.75	12.26
12	1964	30/6 - 08/7	08-7	21.54	17.43	12.90	08-7	26.92	14.02
13		16/8 - 19/8	18-8	24.40	11.59	08.58	19-8	25.36	16.79
14	1965	22/8 - 26/8	25-8	29.81	16.10	11.91	22-8	25.53	13.62
15		23/9 - 29/9	24-9	16.86	08.33	06.17	26-9	13.32	07.15
16	1966	29/7 - 02/8	31-7	14.42	02.38	01.76	31-7	21.42	19.66
17	1967	02/8 - 05/8	03-8	23.52	00.79	00.59	04-8	25.33	24.75
18		20/8 - 26/8	24-8	18.08	11.62	08.60	25-8	22.05	13.45
19	1968	11/8 - 23/8	14-8	20.66	16.63	12.31	16-8	22.90	10.59
20	1969	01/8 - 06/8	02-8	07.91	02.38	01.76	01-8	29.98	28.22
21	1970	30/6 - 11/7	03-7	18.87	00.00	00.00	02-7	25.53	25.53
22		23/8 - 18/9	26-8	13.94	13.15	09.73	28-8	23.75	14.02

Table 1: Continued

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
23	1971	27/7 - 30/7	28-7	23.38	14.37	10.63	31-7	21.71	11.08
24		03/8 - 05/8	03-8	16.18	10.29	07.61	05-8	23.92	16.31
25		30/8 - 02/9	31-8	17.82	12.84	09.50	01-9	21.23	11.73
26	1972	12/9 - 18/9	13-9	11.76	14.40	10.65	15-9	20.83	10.18
27	1973	09/7 - 17/7	10-7	18.36	09.35	06.92	15-7	23.58	16.66
28		19/8 - 22/8	20-8	18.05	11.34	08.39	22-8	21.11	12.72
29		02/9 - 06/9	03-9	18.82	15.27	11.30	06-9	23.44	12.13
30		28/10 – 31/10	29-10	14.45	14.48	10.72	31-10	20.40	09.69
31	1974	17/8 - 21/8	17-8	17.34	12.75	09.44	19-8	22.50	13.06
32	1975	20/8 - 30/8	21-8	22.61	17.09	12.64	23-8	23.44	10.79
33	1976	04/8 - 08/8	06-8	12.64	02.55	01.89	04-8	19.21	17.33
34		11/8 - 18/8	15-8	21.37	07.23	05.35	15-8	25.90	20.55
35	1977	27/7 -02/8	30-7	12.47	06.80	05.03	01-8	13.15	08.12
36		07/8 - 11/8	08-8	17.99	10.40	07.70	11-8	17.80	10.10
37	1978	17/8 - 21/8	18-8	16.63	10.49	07.76	21-8	19.67	11.91
38		26/8 - 03/9	30-8	18.50	11.17	08.26	29-8	28.14	19.88
39	1979	09/8 - 13/8	10-8	15.30	03.77	02.79	10-8	18.90	16.11
40	1980	12/9 - 16/9	15-9	13.15	13.46	09.96	14-9	24.20	14.24
41		19/9 - 30/9	20-9	37.75	33.41	24.72	22-9	35.99	11.27
42	1981	16/8 - 26/8	23-8	13.43	08.78	06.50	24-8	18.90	12.40

43	1982	07/8 - 28/8	19-8	17.00	06.66	04.93	20-8	20.55	15.62
44		30/8 - 04/9	31-8	26.92	00.00	00.00	31-8	44.89	44.89
45	1983	01/9 - 13/9	07-9	15.87	11.93	08.83	09-9	25.56	16.73
46	1984	09/8 - 11/8	10-8	15.73	07.03	05.20	10-8	19.04	13.84
47		16/8 - 25/8	18-8	15.98	11.14	08.24	17-8	25.05	16.81
48	1985	30/7 - 14/8	09-8	14.74	06.91	05.12	07-8	26.35	21.24

Table 1: Continued

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
49	1986	25/6 - 30/6	29-6	24.37	08.73	06.46	29-6	24.65	18.20
50		21/8 - 22/8	22-8	13.04	01.98	01.47	22-8	26.92	25.45
51	1987	28/8 - 31/8	28-8	14.74	00.00	00.00	31-8	05.55	05.55
52	1988	03/8 - 10/8	04-8	13.29	00.00	00.00	09-8	12.47	12.47
53	1989	27/7 - 01/8	29-7	08.08	00.00	00.00	30-7	07.08	07.08
54	1990	29/8 - 10/9	06-9	12.64	09.12	06.75	06-9	24.65	17.90
55		10/9 - 21/9	16-9	15.30	15.22	11.26	17-9	23.10	11.83
56	1991	20/7 - 04/8	24-7	15.22	01.67	01.24	01-8	20.55	19.31
57		12/8 - 21/8	14-8	19.16	02.55	01.89	14-8	36.02	34.13
58		22/8 - 01/9	25-8	14.00	06.43	04.76	24-8	18.14	13.38
59	1992	28/7 - 02/8	30-7	13.49	00.00	00.00	30-7	32.14	32.14
60		16/8 - 30/8	22-8	16.58	02.27	01.68	21-8	31.91	30.23
61	1993	14/8 - 26/8	21-8	11.82	08.56	06.33	21-8	22.10	15.77
62	1994	19/6 - 25/6	21-6	20.63	08.53	06.31	22-6	17.63	11.31
63		08/7 - 19/7	11-7	25.84	17.71	13.11	13-7	29.02	15.91
64		20/7 - 25/7	21-7	19.84	17.97	13.30	23-7	22.93	09.63
65		03/8 - 09/8	04-8	17.77	07.88	05.83	05-8	14.51	08.68
66		18/8 - 26/8	20-8	13.21	02.92	02.16	20-8	22.05	19.89
67		27/8 - 10/9	01-9	17.23	11.00	08.14	06-9	30.63	22.50
68	1995	18/7 - 29/7	26-7	15.61	00.99	00.73	25-7	25.93	25.20

Table 2: Peaks of Inflow Hydrograph into the Reservoir (Thousand Cumecs) of Historical Sixty-eight Floods (1958 - 1995) for Various Block Period

Sl. No. of flood	BLOCK PERIOD									Non-monsoon season
	1/7 – 10/7	11/7 - 20/7	21/7 - 31/7	1/8 - 10/8	11/8 - 20/8	21/8 - 31/8	1/9 - 10/9	11/9 - 20/9	21/9 - 30/9	
	1	2	3	4	5	6	7	8	9	
1	43.22	23.83	14.42	27.49	23.46	15.73	25.79	24.43	16.86	14.4(29.10.73)
2	21.54	23.12	23.83	7.88	18.42	29.81	18.82	19.69		24.37(29.6.86)
3	18.87	25.84	12.47	23.52	24.4	18.08	15.87	11.76		20.63(21.6.94)
4	18.36		8.08	7.91	20.66	13.94	12.64	13.15		
5			15.22	16.18	18.05	17.82	17.23	37.75		

6			13.49	12.64	17.34	22.61		15.3		
7			19.84	17.99	21.37	18.5				
8			15.61	15.3	16.63	13.43				
9				15.73	17	26.92				
10				14.74	15.98	13.04				
11				13.29	19.16	14.74				
12				17.77	13.21	14				
13						16.58				
14						11.82				
MAX	43.22	25.84	23.83	27.49	23.46	29.81	25.79	37.75	16.86	
MIN	18.36	23.12	8.08	7.88	13.21	13.04	12.64	11.76	16.86	
No. of flood	4	3	8	12	12	14	5	6	1	3

Table 3: Data of Severe Floods Among Sixty-eight Floods from 1958 to 1995 in Ten Days Block Period-Wise.

Duration of block period		1st July - 10th July	11th July - 20th July	21st July - 31th July	1st Aug - 10th Aug	11th Aug - 20th Aug	21st Aug - 31st Aug	1st Sep - 10th Sep	11th Sep - 20th Sep	21st Sep - 30th Sep
Block period No.		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Duration of occurrence	Most severe flood	04/07/61 to 13/07/61	08/07/94 to 19/07/94	27/07/71 to 30/07/71	29/07/59 to 07/08/59	16/08/64 to 19/08/64	22/08/65 to 26/08/65	01/09/61 to 11/09/61	19/09/80 to 30/09/80	23/09/65 to 29/09/65
Peak inflow into the reservoir (T. Cumecs)		43.2	25.8	23.4	27.5	24.4	29.8	25.8	37.7	16.9
Peak calculated d/s catchment contribution (T. Cumecs)		13.7	15.9	11.1	05.4	16.8	13.6	24.4	11.3	07.1
Duration of occurrence	Second most severe flood	30/06/64 to 08/07/64	10/07/58 to 22/07/58	18/07/95 to 29/07/95	02/08/67 to 05/08/67	15/08/60 to 19/08/60	30/08/82 to 04/09/82	02/09/73 to 06/09/73	10/09/59 to 18/09/59	No second flood during ninth block period
Peak inflow into the reservoir (T. Cumecs)		21.5	23.8	15.6	23.5	23.5	26.9	18.8	24.4	
Peak calculated d/s catchment contribution (T. Cumecs)		14.2	20.2	25.2	24.7	03.0	44.9	12.2	24.9	

Table 4: Results of Calibration Phase.

Calibration flood No.	P_{QD}:P_{US}:P_{ROAI}:P_{ROAD}: P_{QI},P_{LS},P_{ROEI},P_{ROED}	Performance during the flood operation		
		Maximum Storage achieved during flood (TMCM)	Peak flow at Naraj during flood (T. Cumecs)	Duration of flood control operation from starting of flood (Days)
1	1 : 3 : 1 : 1 : 8	7.197	22.2	11
	1 : 4 : 1 : 1 : 8	7.197	22.1	11
	1 : 5 : 1 : 1 : 8	5.300	24.3	08
	1 : 3 : 1 : 2 : 8	7.197	22.3	15
	1 : 4 : 1 : 2 : 8	7.197	22.3	15
	1: 5 : 1 : 2 : 8	5.340	24.4	08
2	1 : 3 : 1 : 1 : 8	7.197	20.4	08
	1 : 4 : 1 : 1 : 8	7.197	20.1	08
	1 : 5 : 1 : 1 : 8	6.850	20.6	08
	1 : 3 : 1 : 2 : 8	7.197	20.5	10
	1 : 4 : 1 : 2 : 8	7.197	20.5	10
	1: 5 : 1 : 2 : 8	6.900	20.6	08
3	1 : 3 : 1 : 1 : 8	7.197	25.5	09
	1 : 4 : 1 : 1 : 8	7.197	25.5	09
	1 : 5 : 1 : 1 : 8	6.400	25.9	08
	1 : 3 : 1 : 2 : 8	7.197	25.5	10
	1 : 4 : 1 : 2 : 8	7.197	25.6	11
	1: 5 : 1 : 2 : 8	6.4	25.9	08