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FLOOD CONTROL REGULATION OF A MULTI-RESERVOIR SYSTEM

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PREFACE

The Indian climate presents a striking contrast of meteorological conditions as it frequently faces severe floods and acute droughts. Because of the high incidences of floods during the monsoon season, the use of multipurpose reservoirs, with flood control as one of the purposes, is quite common in India. Many approaches are available for the operation of a multipurpose reservoir during the flood season, one of them being separate allocation of storage space for flood control. However, to keep the submergence level at the minimum possible, a number of multipurpose projects are constructed without sufficient exclusive flood storage, thereby necessitating optimum and judicious management of reservoirs during the flood season. The major hydrologic information available to the operator at the time of flood at most of the reservoirs in developing countries is only the inflow rate to the reservoir. Flood situations generally cause panic to the operator and detailed guidelines are needed to successfully operate a reservoir during floods.

In this report, a computer program has been developed to simulate the operation of a multiple reservoir system for flood control regulation. Using the various scenarios of inflow and operation from various control locations, the operation of a system can be analysed and the operation policy for the whole system can be evaluated. The program provides detailed operation table of each structure so that the policy could be refined till the desired objectives are achieved. The program has been incorporated as a separate module of a comprehensive software package "Software for Reservoir Analysis (SRA)" prepared by the Institute. I hope that the package will be useful for the organisations involved in developing the policies for flood control operation of a reservoir or a system of reservoirs.

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ABSTRACT

The purposes which a reservoir is intended to serve is an important consideration in planning and operation of the reservoir. Since the functional, infrastructural and operating requirements of a conservation storage reservoir are quite different from a flood control reservoir, the analysis tools are also different. Moreover, the computational algorithm and data requirements are also different. In view of this, usually different computer models are employed for analysis of flood control and conservation storages although in some models, both capabilities are combined.

A key consideration while operating a flood control reservoir is that the releases from the reservoir should not contribute to flood at important locations downstream, to the extent possible. The reservoirs which exclusively serve for flood control must be emptied as soon as possible so that the next flood, if any, can be moderated to the maximum possible extent.

In India, the emphasis has been on construction of multipurpose projects due to economy of construction cost. In the monsoon climate, these projects have to serve two different objectives. They are required to moderate the incoming floods to the maximum possible extent as well as store enough water during the monsoon period so that the conservation purposes are best served during the remaining period of the water year.

In the present report a software which has been developed for flood control regulation of a system of reservoirs is described. The reservoirs can be gated or ungated and the system can have any combination including weirs and diversions. For operation of reservoirs, the scenario has been divided into two categories depending on the reservoir level and inflows. These categories are normal operation and emergency operation. The input data requirements of the software are modest. This software along with a previously developed software for conservation operation would provide a complete set of tools to analyze any system configuration for the range of purposes for which the reservoirs are commonly built in India.

CONTENTS

1.0 INTRODUCTION

The floods, as commonly understood, are those relatively high flows of water in rivers which overtop the artificial or natural banks and cause damages in populated, agricultural or industrial areas. Floods result from a number of causes -- heavy and prolonged rainfall is the most frequent one. It is helpful to classify floods for their systematic studies. These can be classified as: flash floods, single event floods, multiple event floods and seasonal floods. Flash floods have sharp peak; the rise and fall are almost equal and rapid. Single event floods are those which have a single main peak. These floods have long duration compared to flash floods. Multiple event floods are caused by more complex weather situations. In these floods, successive flood peaks follow closely. The floods which occur in wet season are known as seasonal floods. In some countries, snowmelt also produces frequent flooding. Amongst the floods not directly caused by rainfall, dam-break floods are of great concern. When a dam failure occurs, it accompanies a severe flooding and normally causes considerable damages and loss of life. Tectonic movements introducing landslide into water bodies can also cause floods.

Despite flood hazards, since the dawn of civilization, mankind has shown a preference to settle near the rivers due to assured supply of water, facility of navigation and fertility of river valleys. Even today, a considerable portion of world population lives in areas adjacent to rivers and often becomes victim of misery and upheaval in the wake of devastating floods. Floods have accompanied mankind throughout the history. Accounts of man's struggle with this natural phenomenon can be seen in literature. The actual management of floods, when flooding occurs largely depends on the available local facilities since external aid can't be relied upon. Therefore, it is necessary to plan and execute flood management measures meticulously. The problem is essentially of interdisciplinary nature.

1.1 FLOOD MANAGEMENT MEASURES

The various measures for flood management can be classified mainly as: 1) Short-term & 2) Long-term measures. The nature and extent of flood damages as well as the local situations often suggest the measures to be taken up. The short-term measures are dependent on long-term measures for their effectiveness.

Short-term Measures

These measures which give quick results, are adopted when immediate relief to some pockets or locations is felt necessary. They are

(i) Construction of embankments along the low level banks that are subjected to frequent flood spills.
(ii) Construction of raised platforms for temporary shelter during floods
(iii) Dewatering (by pumps) of flooded pockets, towns and agricultural fields when the flood water cannot drain out by gravity.
(iv) Construction of flood walls near congested areas of towns, cities and industrial belts.

Long-term Measures

These measures have long-term impact.

(i) Construction of storage reservoirs can moderate the flood peaks. They are costly proposition and take long time for investigation and implementation.
(ii) Integrated watershed management projects in the hilly catchments of tributaries go a

long way in controlling the floods in the plains. They reduce the runoff and erosion, increase infiltration and improve the environment and ecology.

(iii) Flood forecasts and warnings are very useful during the flood season. Warning on the basis of hydro-meteorological studies can be given far ahead to minimise loss of life and property by shifting population to safer areas in time.

1.2 FLOOD CONTROL STRATEGIES

The three approaches or strategies to achieve flood loss reduction are:

1. Modify flooding by structural means: The traditional strategy involves construction of dams, dikes, levees, channel alterations, high flow diversions and land treatment measures. The basic idea is to keep water away from the potential damage areas.
2. Flood forecasting (non-structural means): Forecasts of flooding is provided at the potential damage points. The human and animal population and movable property are moved to safer places if there is a likelihood of flood damage. This strategy involves keeping people away from water.
3. Modify susceptibility to flood damage: Making regulations to avoid undesirable or unwise use of flood plains. Steps are also taken to modify the impact of flooding on individuals and the community action designed to assist the individuals in the preparatory, survival & recovery phases of floods. This can be achieved by providing education and information on floods, flood insurance and tax adjustments etc.

1.2.1 Structural Measures for Flood Control

As the name suggests, the structural measures aim to control the flood damages by restricting or regulating the movement of water during flood period. This strategy includes construction of physical components. These are:

a) dams, reservoirs and high flow diversions: to store the flood water temporarily or to divert it away from the area to be protected.
b) embankments, levees and floodwalls: to stop the flood waters from entering the areas which are to be protected.
c) channel improvement works which increase the carrying capacity of a river channel and the flood waters quickly pass the channel reach.
d) catchment treatment to induce temporary holding of water in the catchment.

The embankments as means of protection against flood waters, being the direct, the cheapest and immediately effective method, date back to earliest recorded history. In general, embankments are satisfactory means of flood protection when properly designed, carefully executed and adequately maintained. A suitable combination of this method with other methods, such as storage dams, detention basins etc., is very efficient and durable. In India, embankments have been in use for thousands of years for protection against floods, particularly in delta areas. Most rivers flowing through alluvial plains have protective dykes in some reach or the other, the notable rivers having extensive embankments being Gandak, Kosi, Damodar, Mahanadi, Godavari, Krishna and Cauveri.

1.2.2 Non-structural Measures

The main idea behind this strategy is to keep the life and industrial activity away from the floods. This can be achieved by: Flood forecasting and warning systems, Flood emergency plans; Floodplain regulations through zoning, building codes, flood proofing and other regulatory tools; Disaster preparedness and assistance.

Automatic raingauge stations provide frequent and reliable picture of the situation in the basin. Radar data provide details of dynamics and movements of rainstorms in a relatively larger scale. Meteorological satellite data can constitute a useful part of the inputs to the forecast. Nowadays, real-time flood forecasts are being issued for important rivers in India for operational purposes. The data requirements for forecasting are:

Rainfall flood	Rainfall details, catchment details, river geometry, discharge and water level
Flash flood	Network of gauging and quick transmission;
Snow melt flood	Precipitation, snow cover area, air temperature, wind;

Emphasis on one particular measure alone for tackling the acute flood problem can not provide the desired results. Use of all the strategies of flood management including regulation of developmental activities in the flood plains is very essential.

The expected annual flood damages are normally computed in probabilistic terms. The procedure followed includes routing of the releases from the dam site to the downstream control point where the computed discharge is converted to respective elevations using rating curve of the control point, the cross-section. The inundated areas corresponding to the computed elevation are marked on the map. An exhaustive survey is made in the delineated areas for the census of inhabitants, live stock, valuable properties, industries and other structures of major importance, and valuable agricultural land liable to be affected by the flood. An assessment on the likely damages is made for several flood events and elevation versus annual flood damage curve is plotted. Using long term historical annual flood series, a frequency analysis is carried out and probabilities are assigned to the above flood events observed at the control point. Then a plot between elevation and probability of exceedance is prepared. It is converted to the plot between probability of exceedance and annual flood damages, which can be non-dimensionalized using the potential damage. Thus, a non-dimensional probabilistic damage curve is prepared which is used in release decision making.

2.0 RESERVOIR OPERATION FOR FLOOD CONTROL

Among the measures of flood control, a storage reservoir with gates to control the outflow is perhaps the most effective means. The moderation of a flood through storage is achieved by storing a part of flood volume in the rising phase and releasing gradually the same in receding phase of the flood. The flood control pool operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint that the designed maximum water level is never exceeded. Flood control pool must be emptied as quickly as downstream flooding conditions allow; this will reduce the risk of future highly damaging releases, should a major flood occur.

The regulation consists of storing the peak flows, over and above the safe (non-damaging) carrying capacity of the channel at the damage point, in the reservoir. The reservoir is emptied after the passage of flood to provide empty space for control of subsequent floods. In the Fig. 2.1, ABCDE represents the inflow hydrograph. The line ZZ represents the non-damaging carrying capacity of the river channel downstream to the reservoir. From point B to point D, the natural flow in the river exceeds its safe carrying capacity. If there is no reservoir, from the time corresponding to the point B up to D, the flood water will spill over the channel banks and will cause damage. The regulation of the reservoir for controlling the floods is given by dotted line AGDF. The releases is gradually increased from point A onwards, making sure that at no point the release exceeds the safe carrying capacity. This is achieved by storing the volume between the curve BCD in the reservoir and after point D, the reservoir is gradually emptied.

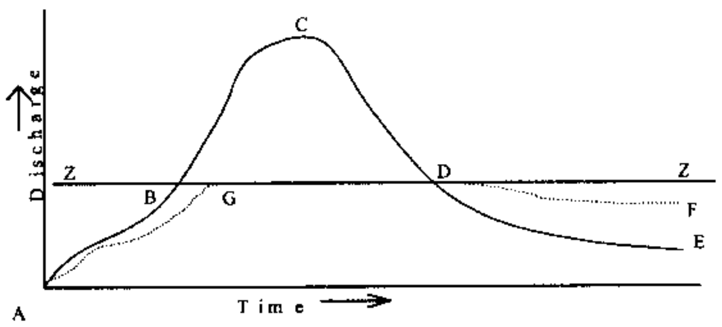

Fig. 2.1 Ideal operation of a reservoir for flood control

The above scenario of operation is an ideal situation which is possible only if perfect fore-knowledge of hydrograph is available. In absence of such information, the release curve may divert from the ideal shape. For example, if the operator makes smaller releases in the early part of the hydrograph, it is likely that the reservoir will completely fill before point D. In that situation, subsequently the operator will be forced to make releases in excess of the safe carrying capacity of downstream channel. Conversely, if at the beginning of a flood event, the operator starts making higher releases in the expectation of a major flood and such a flood does not occur, the reservoir may not fill to the desired level by the end of the wet season.

Two approaches are possible to control flood peaks by the reservoirs. The first consists of operating the reservoir to reduce every flood peak by the maximum possible amount. In the second approach, the attention is focussed on moderation of larger floods; the smaller flood peaks are not given much attention. However, it would be ideal that the reservoir is operated such that release is always less than the safe carrying capacity of the down stream channel.

2.1 Approaches of Reservoir Operation During Floods

The flood control reservoirs are designed to moderate the flood flows that enter the reservoirs. This is achieved by storing a part of inflows in the reservoir and making releases so that the damages in the downstream areas are minimum. The degree of moderation or flood attenuation depends upon the empty storage space available in the reservoir when the flood impinges it.

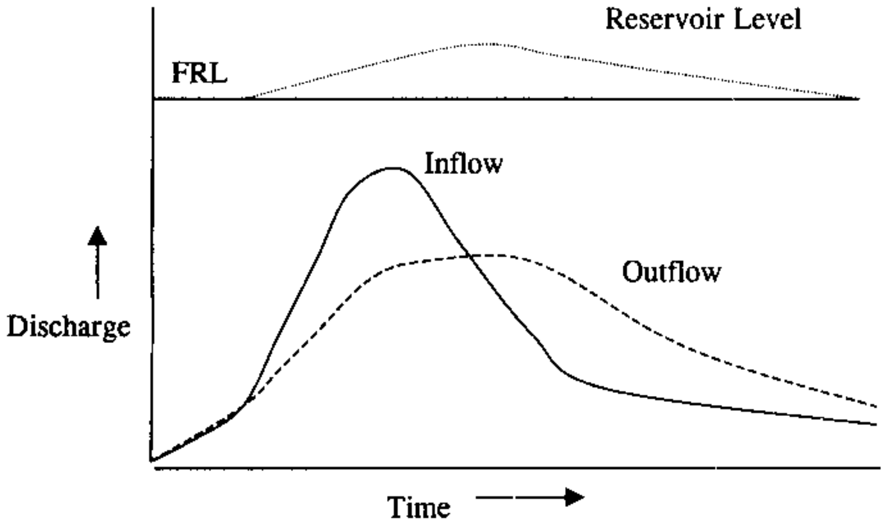

Fig. 2.2a Normal mode of flood control operation of a reservoir

The normal mode of operation of reservoir during floods (see figure 2.2a) is to make releases less than or equal to safe capacity of the downstream channel as long as there is empty space in the reservoir. The reservoir level is allowed to rise above the full reservoir level (FRL). The maximum level up to which the reservoir level can rise is known as the maximum water level (MWL). The zone between the FRL and MWL is normally exclusively reserved for flood control. After the flood has peaked, the reservoir is gradually bought back to FRL.

There may be situations when it is not desirable to allow the reservoir level to rise above the FRL (see Fig. 2.2b). In that situation, the outlet capacity to be provided should be large, preferably equal to the maximum expected inflows. Alternatively, the reservoir level is lowered by making pre-releases in anticipation of floods. The level is brought back to FRL after the peak is passed. This strategy involves use of inflow forecasts and therefore, the confidence of the operator in making pre-releases depends on the reliability and timely availability of forecasts.

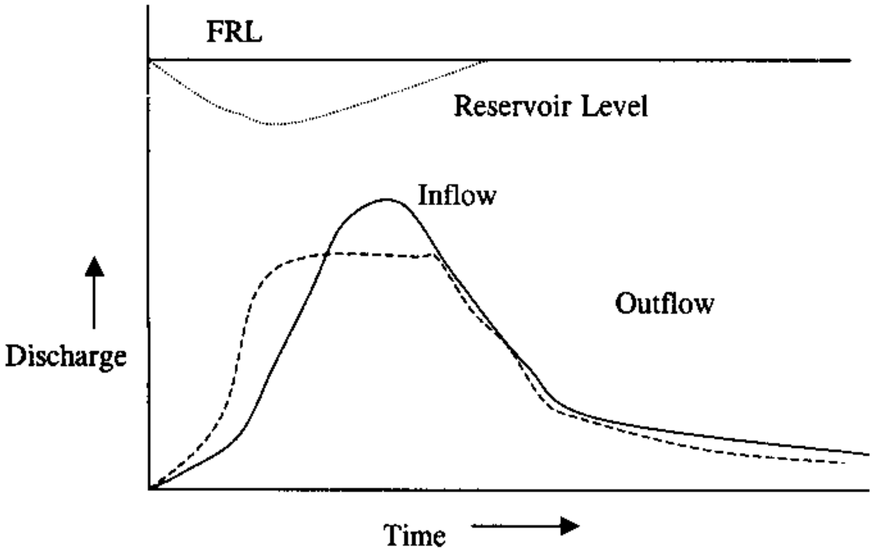

Fig. 2.2b Flood moderation through reservoir pre-depletion

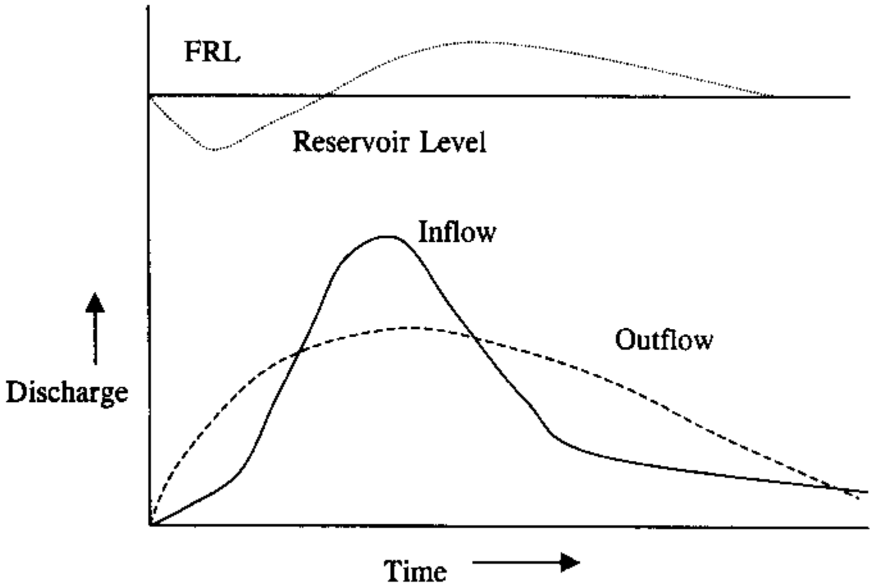

Fig. 2.2c Flood moderation through pre-depletion and use of flood control space

There is a possibility of a third situation in which the reservoir is at or below the FRL at the beginning of flood control operation. The operator has an option of lowering the reservoir level by pre-releases to create storage space for flood moderation. The reservoir is operated such that the reservoir level reaches the maximum permitted water level (MWL) during the passage of the flood (see Fig. 2.2c). Thereafter, post releases can be made in such a manner that the reservoir comes back to the level from where it started. Thus, the flood is moderated using the space created by pre-releases and the space between FRL and MWL. If not constrained by other factors, this approach perhaps involves making most efficient use of the reservoir storage space.

2.2 Operation of a Multipurpose Multi-reservoir System

In case of multipurpose reservoirs whose main purpose is flood control and which are located in the regions where floods can be experienced at any time of the year, permanent allocation of the space exclusively for flood control at the top of conservation pool is necessary. The size of flood control space may vary with time according to the magnitude of floods likely to occur. The flood storage space allocation at different times of the year is so determined that incoming floods would be absorbed or mitigated to a large degree. Even if a maximum probable flood is likely to occur, its peak should be substantially reduced and flood damage on the downstream should not exceed the permissible limits. In regions where floods are experienced only in a particular season or period of the year, seasonal allocation of space for flood control is made in reservoirs depending upon the magnitude of floods likely to occur in that period. In non-flood season, this space is utilized for storing water for conservation uses.

The fundamental purpose of a multi-purpose reservoir whose primary objective is flood protection is to moderate potentially dangerous flood flows. Water can be stored in the joint use space of a reservoir for other purposes as long as the flood control operation is not hindered. Water stored for conservation purposes is released depending upon the demands. Before the onset of a flood, the main decisions facing the operator's concern are the amount of flood control space that ought to be available at any time and the size of the releases required to create additional space, if necessary.

The reservoir operation should also include the periodic assessment of future incoming volumes based on the rainfall information gathered from the raingauge stations in the catchment. The frequency of such review is a function of the catchment size and storm properties. In reality, the release decisions are based on intuition and judgement of operator as the information on the likely inflows is usually not available. Therefore, there is a pressing need to develop a strategy for operating the reservoir based on the information on current inflow magnitude and its characteristics and current storage level.

2.3 SOME ISSUES IN RESERVOIR OPERATION

According to James and Lee(1971), the following six issues need to be optimally resolved while developing operation policy of a reservoir:

1. Use of Flood Storage: Whether flood inflows should be stored to reduce current damages or released to provide additional storage space in case new rains produce even greater flows.

2. Use of Total Storage: Whether storage space should be filled to save water for beneficial use or emptied to contain potential floods.

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.

4. Release by Reservoir: How much of the water to be released for beneficial use should come from each reservoir in which water is stored.

5. Use of Available Water: How the water released from the reservoir should be divided among the various potential uses.

6. Release Elevation: Whether the released water should be taken from near the surface or from some elevation deeper within the reservoir.

Out of these six issues, the last two are not relevant for flood control operation. The third factor assumes importance in case of shortage of water. The first, second and the fourth issues are discussed in the following.

2.3.1 Use of Flood Storage

The first important decision while regulating a reservoir is whether the flood flows should be stored in the reservoir to control the current damages or released to provide additional storage space in case a bigger flood arises. This question arises when the storage level in the reservoir is in the flood control zone. The controlling parameters are the available flood storage, the current and forecasted inflows and the status of other reservoirs in the system. While making the releases, the current flow at the damage center and the likely contribution from the catchment downstream of the reservoir up to the damage centre should also be considered. It might be prudent to release at a rate equal to safe capacity of the downstream channel less local flows if there is any water in the flood storage zone. If the forecast indicates possibility of larger floods, releases slightly exceeding safe carrying capacity of the downstream channel can be made to avoid severe damages subsequently. Two main objectives are: (i) to minimize downstream damages and (ii) to ensure dam safety. The economic trade-off is between the increase in downstream damages caused by larger releases and the increase in the expected value of future damages caused by less storage space available to contain the subsequent flows. To meet the trade-off, the operator should have prior assessment on the likely flood damages which can be caused in the downstream area by high releases from the reservoir.

Reliable precipitation forecasts are usually not available to the operators. Therefore, the procedure normally adopted is to develop flood control regulation schedule for a reservoir based on the current inflow rate, reservoir elevation and rate of rise/fall and volume of inflow that can be expected in a flood.

2.3.2 Use of Total Storage

The next important question is whether storage space should be filled by storing water for some future beneficial use or be emptied to absorb likely floods. This question primarily deals with the operation of a reservoir in monsoon season. The objective is to moderate the potentially dangerous floods whenever there is a significant probability of their occurrence and to store water to the capacity of the reservoir for beneficial use in the non-monsoon season. The controlling parameters are the amount of water currently in storage, the vacant space for flood control, the value of stored water and the risk of flood.

In India, reservoirs are generally kept empty in the first few weeks of the flood season and are gradually filled up as the flood season progresses. Usually the rule curves are designed so that the reservoir is full at the end of the monsoon season. However, when the monsoon does not develop as expected or if it withdraws earlier than expected, the reservoirs may not be filled to the maximum possible extent. Clearly, a better strategy would be to fill the reservoir sufficiently at the first available opportunity. If a larger flood is expected subsequently, the storage should be depleted to create requisite vacant space. The storage should again be filled up whenever the flood begins to recede. This procedure can be carried out very effectively if reliable forecast of rainfall and inflows are available.

The release decisions should be taken to ensure that the releases are neither high nor excessive and the reservoir should be full at the end of the filling season. The economic trade-off is between the value of the additional water stored within the reservoir and the additional flood damages if the storage space is not available when flood occurs. Water can be stored in the joint use space of a reservoir for other purposes as long as the flood control operation is not hindered. Water stored for conservation purposes is released upon demand. Thus the main operating decisions facing the operator's concern are the amount of flood control space that ought to be available at any time and size of the releases required to create additional space, if necessary.

2.3.3 Release by Reservoir

The fourth question pertains to the apportionment of release among different reservoirs. How the water to be released for beneficial purposes should be divided among the reservoirs ? For flood control purposes, this will depend upon the vacant storage space available in the reservoirs, conditions in the downstream reaches of each of the reservoir as well as the likely inflow to each of the reservoir. For the best results from the operation of a reservoir system, it is necessary that the operation policies are jointly developed. A telemetry system should be installed so that the forecasts are available in real-time during the flood season.

2.4 FLOOD CONTROL RESERVATION DIAGRAM

The objective of deriving these curves is to define the amount of vacant storage space to be kept available to control the floods of known or generated magnitude over a specified time interval. In calculating the amount of space required, it is assumed that releases in excess of channel capacity will not be made. The vacant space required on any date is the difference in the volume of inflow between the date in question and the date of maximum storage (end of monsoon) and the volume of water released from the reservoir. In order to derive parameter curves for the first day of the various fortnights during the monsoon season, the historical record is routed through the reservoir. The amount of storage space required to control the runoff after the date in question is plotted for each year. A parameter line is then fitted through the points for the date in question. The positive values indicate the vacant space that must be kept available in addition to the minimum flood control reservation. Years having negative values of required space indicate that the flood could have been controlled with less than the minimum flood control reservation.

The flood control space requirement, in general, shows a straight line relationship with the remaining season runoff. The generalized equation is:

$$Y = mX + C_t \tag{2.1}$$

Where, Y is the required space (MCM); m is the tangent of the straight line; X is the remaining season runoff (MCM); C_t is the ordinate intercept (MCM) which is a function of the time (day of the monsoon season). The flood control space requirement can be calculated by the above equation or by graph. If this space is not available on the given date, one must make releases sufficiently large so that enough vacant storage behind the dam is made available. Depending on the inflows, this release may or may not exceed the daily normal outflow required to meet the conservation demands. The flood control reservation chart does not indicate the size of the release to be made. It only indicates the maximum release which is based on the downstream channel capacity. The decision concerning the rate of release will depend on the actual inflows. If the encroachment is small and the inflows are not likely to increase rapidly for some time, the release may be set to draw down the encroached space gradually. This will save water, particularly if subsequent runoff is small. If, however, the inflows are likely to be large, the reservoir will be drawn down rapidly.

As the monsoon season progresses, the runoff generated between the current time and end-of-monsoon and hence the flood control reservation decreases. It implies that the reservoir can be filled and the objective of having the reservoir full at the end of the monsoon season can be satisfied. In other words, the amount of joint storage space committed to flood control decreases as the season progresses and the amount of joint storage space committed to conservation increases. At the end of the monsoon season, the entire joint-use storage space is committed to conservation.

2.5 SYSTEM ANALYSIS TECHNIQUES

Determining reservoir operation policy for the efficient management of available water is a complex problem because it involves random hydrologic events. Many attempts have been made to solve this problem using optimization and simulation models. Reservoir optimization models allow the user to generate operating decisions that are optimal in some "measurable" sense. The optimization models are based on some type of mathematical programming technique. Simulation involves experimentation in order to analyze and evaluate the performance of the system under changing conditions. A simulation model cannot generate an optimal solution to a reservoir problem. However, by making a number of runs of the model with alternative decision policies, a (near) optimal solution can be arrived at. Maass et al. (1962), Loucks and Sigvaldason(1980), Wurbs (1996) and many others have discussed the optimization and simulation models and their underlying differences at length. Wurbs (1996) presented an annotated bibliography of optimization and simulation models.

2.5.1 Optimization

The Linear Programming (LP) and Dynamic Programming (DP) optimization techniques have been extensively used in water resources. Loucks et al. (1981) have demonstrated examples of applications of LP, Non-linear programming (NLP), and DP to water resources. Yakowitz (1982) reviewed the DP models used in various water resources planning problems. Yeh(1985) presented a state-of-the-art review and discussed in detail the various optimization models for multipurpose, multireservoir operation problems. Simonovic (1992) provided a state-of-the-art review of reservoir system analysis and discussed the applications of system approach to reservoir management and operation. Wurbs(1993) reviewed optimization, simulation and network-flow models for various decision making situations.

Young (1967) was the first to propose the use of a linear regression procedure to find general operating rules from deterministic optimization. He derived regression equations using inflows and storage to find optimal releases. Karamouz and Houck(1987) derived general operating rules using deterministic DP and regression (DPR). The DPR model incorporates a multiple linear regression procedure suggested by Bhaskar and Whitlach(1980).

The optimization models are frequently used in the reservoir operation studies employing flow forecast as input. Datta and Burges(1984) derived a short-term operation policy for multipurpose reservoirs from an optimization model with the objective of minimizing short term losses. They examined sensitivity of various performance criteria for the operation of a single reservoir to the accuracy of forecast streamflow volumes. The study revealed that when there is a trade-off incurring one unit of storage deviation and one unit of release deviation from respective target values, the optimized solution depends on uncertain future streamflow as well as the shape of loss function.

2.5.2 Simulation

A simulation model attempts to duplicate the response of the (simplified representation of) system under a given set of conditions. The simulation models associated with reservoir operation include mass-balance computation of reservoir inflows, outflows and changes in storage. They may also include economic evaluation of flood damages, hydropower benefits, irrigation benefits, and other similar characteristics. These models are often used with historical record or critical period data. The simulation technique has provided a bridge from early analytical tools for analysing reservoir storage capacity and operations (such as Rippl diagram or sequent peak) to complex optimization tools. James and Lee(1971) have termed simulation as the most powerful tool to study complex systems.

Examples of simulation date back to the early 1950s. The first contributions were produced by the Harward Water Program (Maass et al., 1962). Probably the most popular and widely used generalized reservoir system simulation model is the HEC-5 model developed by the Hydrologic Engineering Center (see Feldman, 1981; Wurbs 1996). Some other well-known simulation models are: the Acres model, Sigvaldson (1976); the MITSIM model, Strzepek et al. (1979); the Streamflow Synthesis and Reservoir Regulation (SSARR) Model (USACE, 1987), the Interactive River System Simulation (IRIS) model (Loucks et al, 1989; 1990) and the Water Rights Analysis Package (WRAP), Wurbs et al. (1993). Lund and Ferriera(1996) applied deterministic DP to Missouri river reservoir system and found simulation models to be superior to classical regression techniques for inferring and refining operating rules derived from deterministic DP. Despite the availability of several generalized models, the need to develop simulation models for specific reservoir system is usually present as each reservoir system has some unique features.

In view of the versatility of the technique and power of simulation models, it was decided to develop a generalized simulation model for flood control simulation of a multipurpose reservoir. Earlier, a model for simulation of conservation operation of the system has been developed at NIH. This model has been used in studies at NIH and is also being used in many field organizations in India.

2.6 SOME FLOOD CONTROL RESERVOIRS OF INDIA

There are about 3000 major and medium dams in India. To harness the maximum potential of available water resource, an efficient management of these river basins and reservoirs is necessary. Furthermore, there are several inter-state river water disputes and there are many proposals for inter-basin water transfer. The proper distribution and sharing of water requires optimal reservoir operation policies. However, this task is accomplished to a limited extent and for only a few reservoirs. Some important flood control reservoirs of India are described in brief in the following.

1. Damodar Valley Corporation System

The Damodar Valley frequently experiences floods. The flood of 1943 caused extensive havoc in the valley and led to the construction of several reservoirs. Despite the availability of elaborate regulation rules, these reservoirs have not yet been able to afford full protection from flood control. Filling schedules are based on the inflows of 75% and 90% dependable years. The rule curves corresponding to 75% and 90% dependable flows are known as curves A and B, respectively. A strategy is drawn to reach monsoon storage at the end of September. The reservoir is operated near curve B in July and August and switched over to guide curve A in September. This strategy provides an additional flood control space in July, August and to some extent, in early September.

2. Hirakud Reservoir

The Hirakud reservoir across River Mahanadi is operational since 1956. The reservoir has a live storage capacity of 0.582 million ha-m. The FRL and the minimum drawdown level (MDDL) are 192m and 180 m, respectively. It serves three purposes: flood control, power, and irrigation. There is no exclusive storage for any of these purposes; it is shared among the purposes. The flood producing storms originate in the Bay of Bengal and travel from the head of delta towards the catchment. It helps avoid the synchronization of floods from the catchment upstream and downstream of the dam though the flood period gets prolonged.

The main aim of the reservoir is to absorb floods. Hence, it is then depleted after each flood so that vacant space is available when the next flood strikes. To meet the post-monsoon requirements, the reservoir should be filled to the capacity by the end of monsoon. The operation during flood season requires the establishment of a rule curve indicating upper limits of storage levels for conservation. The space between the rule curve and the full reservoir level on any date represents the flood control reservation which is to be utilized during the passage of floods. The flood control space goes on reducing with time during the filling season and reaches zero at the end of the season. Such a rule curve was derived with the following objectives:

(i) The rule curve should be such as to ensure filling of reservoir to levels significantly higher than actually attained in 1974 flood season.

(ii) The maximum regulated discharge at Naraj is to be limited to 31050 cumec as far as possible and this stage should be restricted to 3 to 4 days as prolonged high stages are considered dangerous for the flood protection embankments.

The operation of the reservoir according to the rule curve has resulted in significant improvement in the overall project performance.

3. Ukai Reservoir

The Ukai reservoir is located in Gujarat across River Tapi and has a gross storage capacity of 0.8511 million ha-m at full reservoir level (FRL) 105.156 m (345 ft). The project originally stipulated irrigation and power generation benefits, and partial protection from flood to the city of Surat and other vulnerable areas downstream of the dam, up to a flood discharge of 0.36 lakh cumec. To protect the downstream areas, the current reservoir operation strategy restricts reservoir release to 0.24 lakh cumec (safe carrying capacity of the river) by filling the reservoir to 102.718 m by the end of August. The reservoir is filled up to the FRL (105.156 m) by the end of September. If a flood equivalent to PMF impinges the reservoir at this level, the releases from the reservoir would rise up to 0.29 lakh cumec at the reservoir level 106.985 m and would cause flooding of downstream areas. A big flood occurred in the Tapi basin 1998 and the Surat town remained submerged for more than a week.

3.0 DEVELOPMENT OF FLOOD CONTROL STRATEGY

In this report, a rational approach for operation of reservoirs for flood control is described. The operation of a reservoir for flood control begins as soon as the water level in the reservoir exceeds the rule level for that period. The proposed operation policy for flood control regulation of a reservoir is based on the concept of a cut-off reservoir-level, cut-off inflow magnitude and the nature of inflow (whether rising or falling). The methodology to derive the policy is based on simulation analysis of the system.

3.1 OBJECTIVES

While developing the regulation policy, it is assumed that the operator has the following objectives:

a) To attain the FRL at the earliest and to maintain it;
b) To allow the reservoir level to rise above High Flood Level (HFL) for the least possible time;
c) To release water at rates above non-damaging discharge in the downstream reaches for the least possible time; and
d) To utilize the reservoir storage capacity fully before releasing water at a rate greater than the safe channel capacity.

3.2 APPROACH

In India, real-time telemetry system is not available for most of the reservoirs. Hence, the decision making should be based upon indicators which the operator at the dam site can easily observe. These are: a) the current reservoir level and its rate of rise, and b) the inflows and their trend (whether these are increasing or not). Based on the indication, if necessary, one should immediately trigger the flood control mode of operation of the reservoir.

For development of the operation policy, two parameters need to be defined. The *reservoir critical level (RCL)* is a level in between the FRL and the MWL. If during the passage of a flood wave, the reservoir level rises above this critical level, it indicates that the normal operation procedure has not been able to contain the floods within the desired range. This could be due to limitations of storage capacity or outlet release capacity or because the flood is of a magnitude higher than anticipated. As a very high water level in the reservoir can endanger the safety of the structure due to overtopping etc., it is necessary that the reservoir level is brought down below RCL at the earliest. To do that, the operator may be forced to make releases which may cause damages in the downstream reaches. The *critical flood inflow (CFI)* may also be defined in a similar way and indicates abnormally high inflows to the reservoir. If the actual inflows are higher than the critical flood inflow at any stage, and the reservoir level is above RCL, emergency operation schedule should be followed without any delay.

No simple analytical technique is available to determine the RCL and CFI for a reservoir. These two parameters depend on the reservoir capacity, particularly between FRL and MWL, the capacity of spillway and other outlet works, the volume under the design flood hydrograph and the peak of design flood. These two parameters can be obtained through a trial and error approach using a developed program. As a rough guide, the initial value of RCL may be taken as half way between FRL and MWL and the CFI equal to the safe carrying capacity of the downstream channel. Simulation of the operation of the reservoir is then carried out with either the design flood hydrograph or the hydrograph of a major flood that has occurred in the past. The detailed working table should be printed and should be examined to flag the periods during which the reservoir level was above HFL and the releases were more than the safe carrying capacity of the downstream channel. The parameters RCL and CFI are now modified to best attain the objectives defined in section 3.0 and the program is run again. It has been experienced that the convergence is rapidly achieved within a few runs of the program. In case a system of reservoirs is being analysed, this procedure should be carried out first for individual reservoirs. After these two parameters have been obtained for each individual reservoir, the entire system should be analysed. At this stage, the parameters for individual reservoirs may have to be changed little bit so that the overall performance of the system is the best in terms of the objectives of section 3.0.

In the present methodology, the reservoir operation scenario is classified into two categories: *Normal Operation* and *Emergency Operation.*

3.2.1 Normal Operation

The normal operation of the reservoir for flood control begins as soon as the first signs of an impending flood event are noticed. Specifically, the normal operation policy is applicable when

1. The reservoir level is in between FRL and RCL and the inflow rate is less than CFI, or
2. The reservoir level is in between FRL and RCL and the inflow rate greater than CFI but it is decreasing, or
3. The reservoir level is greater than RCL, the inflow rate is less than CFI and it is decreasing.

Under the normal operation, water is released at a rate which is less than or equal to the safe carrying capacity of the downstream channel. The aim is to bring the reservoir back to the FRL at the earliest so that the reservoir can moderate the next flood, if any.

3.2.2 Pre-depletion of Reservoir

In some reservoirs, the space available for flood control is quite small compared to the volume of design flood hydrograph. Sometimes, it is desirable that the rise of the reservoir level above the FRL should be restricted (see section 2.1). In such situations, pre-depletion of reservoir level below FRL proves to be useful for flood moderation. The important considerations here are:

a) When the pre-depletion should commence?

The pre-depletion should begin as soon as the (expected) inflows exceed a specified value. This value will vary from reservoir to reservoir. As a guideline, it could be about 10% of the minimum of the outlet capacity at FRL and the safe carrying capacity of the downstream channel.

b) How much the reservoir level should be depleted?

Usually, the reservoir levels are depleted by 0.5 to 1.0m below FRL. However, the extent of pre-depletion will depend upon the current reservoir level, rate of inflow and rate of their increase and an estimate of *net* rainfall in the catchment. The net rainfall in the catchment provides an estimate of the volume of the expected inflows to the reservoir. This volume should always be sufficient to fill the reservoir back to FRL if the flood does not develop up to the expected extent.

c) At what stage after passage of flood, the reservoir should be filled back to FRL?

It would be necessary to have an estimate of the *net* rainfall in the catchment at each time step (usually 1-3 hour). This would give the volume of expected inflows. The reservoir re-filling should commence whenever the expected inflows are little more than the volume required to re-fill the reservoir up to the desired level.

3.2.3 Emergency Operation

This mode of operation will be invoked when the flood build-up is of an order which is more than the anticipated and the normal operation has failed to control it. Either the reservoir level is already very high or the inflows are very big indicating the likelihood of an extreme flood. Under the emergency operation, the safety of dam becomes paramount because either the reservoir level is very high or due to big inflows, there is a likelihood of overtopping. The emergency operation policy is followed when

a) The reservoir level is greater than RCL and the inflow rate is less than CFI but it is increasing, or
b) The reservoir level is greater than RCL and inflow rate is greater than CFI though it is decreasing, or
c) At any reservoir level, inflow to the reservoir is more than CFI and it is increasing.

In such cases, if the release at the rate of safe carrying capacity is likely to cause overtopping, release is made equal to the outlet capacity at the current elevation. The objective is to bring the reservoir down to safer level at the earliest and thus avoid overtopping of the dam. The minimum rate at which water will be released from the reservoir under emergency conditions is minimum of the inflow rate and the capacity of outlets.

3.3 SOFTWARE FOR ANALYSIS

A computer program has been developed to simulate the operation of the reservoir for flood regulation using the above approach. The flood hydrograph, conservation rule level, normal values of monthly evaporation, elevation-area-capacity-spillway rating table, and the safe carrying capacity of the downstream channel are input to the program. This simulation program routes the flood through the reservoir and computes the release to be made from the spillway, evaporation losses and the level of the reservoir for each time period. If the reservoir level goes beyond the HFL, the program issues a warning to that effect.

For each storage location, the model operates the reservoir in accordance with the approach described above. The reservoir release is routed down to the next location. Detailed simulation table is also prepared, if desired. Based on the observation from the simulation tables, variables RCL and CFI can be modified till the optimum results are achieved.

3.4 DATA REQUIREMENT OF THE MODEL

The data requirement of the model is quite modest and such data are easily available with the dam operating authorities. Some data pertain to the information about each structure viz. full reservoir level, dead storage level, elevation-area-capacity table, various demands from the reservoir during the monsoon season and minimum flow requirements in the downstream channel, evaporation depths and local inflow from the intermediate/free catchment area. Some data like defining the configuration of the system and the trial rule curve are specified by the user. Description for defining the configuration of the system is as follows:

3.4.1 Configuration of the System

It is generally a healthy practice to prepare the line diagram of the system under study. This line diagram should highlight the location of reservoir, diversion weirs/barrages and the location and direction of the connecting rivers and streams. For defining the system in the model, node numbers are assigned to each structure starting from the upstream structure. The node numbers are assigned in numeric starting from 1. Take care such that all downstream structures should have node number higher to that of their upstream structures. The model recognizes each structure by its node number. Location of each structure is recognized from the node numbers of control points just upstream of the present location. In this way, the configuration of the system is read by the model. For each location, the model reads the name of the structure, its node number, number of nodes immediately upstream of the present node and their node numbers.

The model can be used for a system having any number of control points. If the number of control points in the system is larger than the dimensional limits specified, the parameter *I1* of the program should be increased.

For defining initial conditions at each location, data in the form such as initial year, initial month and initial storage in each storage location is specified. The time-step size for the simulation usually varies between 1 to 6 hours. In the model this is read as input.

3.5 OUTPUT OF THE MODEL

The model simulates the operation of a system of reservoirs, weirs and diversions for the specified period. A detailed working table is prepared for each structure. The model calculates the monthly time and volume reliability for each structure. In addition, it also calculates the total number of months of failure, irrigation or power failure and water supply failure.

In addition to calculating the reliability, a detailed operation table for each structure is optionally prepared. For each period, the table gives the year, month and period of operation, the initial storage, flow from intermediate catchment, evaporation, irrigation, water supply, hydropower and downstream demands, release made, power generated, spill from the structure, end level and middle and upper rule levels. Based on the observations from the tabular presentation, rule curve levels in particular period can be modified till the best operation performance is achieved.

3.5.1 Graphical Presentation

A module for presenting the operation results in the graphical form has been added in the program. For each control point in the system, four types of graphs can be prepared. These are: plot of reservoir inflow versus release, plot of reservoir level vs. rule level, plot of reservoir storage vs. inflow and plot of demand vs. release. Based on the visual inspection of results also (in addition to the tabular form), the controlling variables at a location can be revised and policies for better management of the system can be developed.

3.6 STEPS FOR MODEL APPLICATION

The recommended steps to be performed for applying this model to a system and for deriving the optimum rule curves are as follows:

1. Prepare the diagram of the system showing the name of reservoirs and diversion weirs/barrages, their location and the length and direction of the rivers and tributaries.

2. Give node numbers in numeric form to all the control points (storage reservoir, diversion weir, barrage etc.) starting from the upstream node. Take care to see that node number of a particular control point should always be higher than that of all the structures situated upstream.

3. Collect and input general details about the operation like the number of control locations in the system, initial month, day and hour and total number of periods of operation.

4. Collect and input general details about each location which include maximum capacity up to the full reservoir level, initial storage, elevation-area-capacity table, demands, minimum release to be made in the downstream channel and the evaporation depths for all the months of the year.

5. For each structure, calculate the local flow coming from the free catchment area at that structure for all the periods of operation. If inflow is to be obtained by multiplying the inflow data of some other structure by some number, then the node number whose data are to be used for calculation of local inflow at present structure and the multiplication factor needs to be mentioned in the data file. If routing is to be performed than supply the values of required parameters.

6. Simulate the operation of the system. Find the periods in which releases were high. Adjust the values of RCL and CFI for the corresponding reservoirs and run the model again. Repeat this procedure till the required results are obtained.

3.7 DESCRIPTION OF THE PROGRAM

The present program has been written in the FORTRAN language. The program consists of a main program, one subroutine for simulation of operation of a structure (subroutine *OPER*) for a particular period, subroutines for reservoir routing and channel routing, a subroutine (*RESULT*) for tabular presentation of the results and a subroutine for the graphical presentation of the results.

The entire input data are read by the main program. Several checks have been introduced to detect the likely errors while preparing the input data. After reading a group of data items, the program displays a message on the screen showing that the corresponding data items have been read properly. This facility is immensely helpful in locating the possible error as the user knows that for which structure and at which group of data, the error is encountered. The program reads in the entire data for a structure at a time.

After reading the input data, a loop which goes for all time periods is run. Inside it, another loop runs for each location. The operation subroutine *OPER* is called for each reservoir or diversion structure. If the location is a ungated dam, instead of *OPER*, the reservoir routing routine is called. If flow is to be routed from this structure to the downstream node, the channel routing routine is called.

After the simulation of operation for the whole system is over, the subroutine *RESULT* is called and the results in are written in tabular form for each structure. Next, the *GRAPHICS* subroutine is invoked by the main program. If the user wishes to have graphical presentation of the operation of a structure, he is asked to choose the location. Four types of graphs can be plotted and the user is prompted to enter the corresponding code.

***

4.0 SAMPLE INPUT FILE

A sample input file for the program is shown in appendices. The data for a hypothetical system is used for demonstration. This system consists of two streams which join at a Y-junction. One stream has two reservoirs in series, the other has an ungated dam. A diversion weir has been constructed after the junction. The line diagram of the system is presented in Figure-1. For the convenience of the users, the input file is shown, in the variable form in Appendix-1. A listing of the input section of the programme is shown in Appendix -2. A listing of the sample input file with actual values for the hypothetical system is given in Appendix-3.

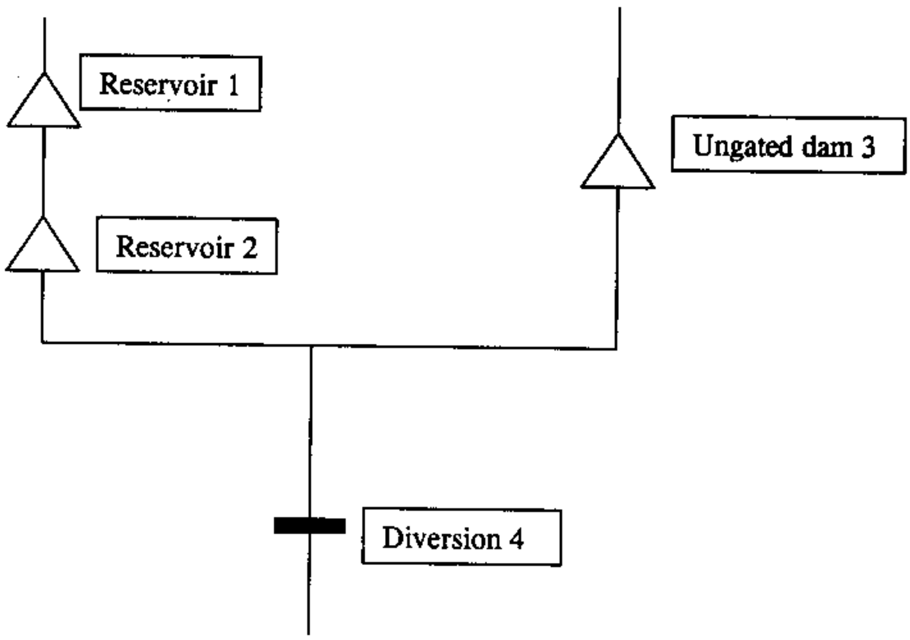

Figure 1 Line diagram of the hypothetical example system

4.1 SAMPLE OUTPUT FILE

The output file for the simulation of the hypothetical system whose input data file is given in Appendix-3 is shown in the Appendix-4.

In the reservoir working table, the last column 'case' indicates the reason behind making the release. The following table explains the meaning of the various notations used:

CASE	EXPLANATION
BRUL	Initial reservoir level below rule level
RuFr	Initial reservoir level between rule level and FRL
FrI+	Initial reservoir level between FRL and RCL, inflow increasing
FrI-	Initial reservoir level between FRL and RCL, inflow decreasing
EmI+	Emergency operation, inflow increasing
EmI-	Emergency operation, inflow decreasing

***

5.0 CONCLUSIONS

In India, about 80% of the annual rainfall takes place in the 4 months of monsoon season. Due to this, many rivers experience flooding during this period. Reservoirs are one of the structural measures which are used to manage the floods. These can be very effectively used if proper policies for their operation are available.

While operating a flood control reservoir, the objectives are : a) to allow the reservoir level to rise above High Flood Level for the least possible time, b) to release water at rates above non-damaging discharge in the downstream reaches for the least possible time, and c) to fully utilize the reservoir storage capacity before releasing water at a rate greater than the safe channel capacity.

This report describes a software which has been developed to assist in preparing reservoir operation policies for flood control such that these objectives are attained to the best possible extent. The use of the software has been demonstrated with the help of the data of a real-world system.

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INPUT DATA FILE IN VARIABLE FORM

Line No.	Variable	Description
1	Titl	Title of the problem
2	NLOC ih(0) iday(0) imon(0) nmon dt	No. of locations Initial hour Initial day Initial month No. of periods time step in hours
For each location		
3	name(i)	Name of location
4	icp(i), icp1(i) (icp2(i,j),j=1,icp1(i))	ID No. of control point (CP) No. of points upstream of CP ID of icp1 upstream points of this CP
5	smax(i) smin(i) stor(i,1) nn(i) gfac(i)	Max storage capacity (m^3) Dead storage(m^3) Starting storage (m^3) Points in EAC Table (= 0 for non-reservoir locations) gfac = 0.1 to 1 for storage dams and the spillway capacity is multiplied by gfac to get effective spillway capacity, = 2 for diversions and = 3 for ungated dams
6	**Only if gfac is less than 1** frl(i) chcp(i) rcl(i) cfi(i) rinc(i)	 Full reservoir level (m) Safe capacity of downstream channel (cumec) Reservoir critical level (m) Critical flood inflow (cumec) level (m), Maximum permissible change in release in consequtive periods, given as fraction
7:nn(i)+7	For storage/ungated dams only elev(i,j) area(i,j) cap(i,j) relc(i,j)	 Elevation (m) Corresponding area (m^2) Corresponding capacity (m^3) and Corresponding release capacity (cumec)
Next	infl fac(i) amflo(i)	=1 inflow data is input, =2 computed using other location data; Inflows read (local or at LOC j) will be multiplied by this factor Min. release to be made in Mm^3

	irout(i) idp(i)	= 0 - no routing, =1 - release to be routed to next downstream location =1 if detailed results for this node are needed
Next	(rule(i,j),j=1,12)	Rule curve levels for 12 months (m)
Next	(evpd(i,j),j=1,12)	Evaporation depth in m/month
Next	Only if irout(i)=1, imeth(i)	Flood routing method, 1 for Muskingum
Next	Only if irout(i)=1, ak(i), ax(i)	Muskingum parameters k,x
As needed	(flow(i,j), j = 1, nmon) or inod	Inflows for nmon periods (cumec) or The ID of node whose flows will be multiplied by fac to get flows at this node.

Note: The entire data for each structure is entered at a place.
Before entering the name of a subsequent structure, leave one line blank.

Listing of Input Section of the Programme

```
C***  I N P U T   B L O C K

C***    General Information of the System
c***    Titl - Title; nloc - No. of Locations; imon(0) - Initial Month
c***    ih(0) - Initial Hour; nmon - No. of periods, dt = time step in hrs
      read(1,1) Titl
      write(2,1) Titl
      read(1,*) nloc, ih(0), iday(0), imon(0), nmon, dt
      write(2,'(/'' Time-step size for simulation ='',f4.0'' Hr'')')dt
      dts = dt*3600.0


c***    Data related to Configuration
C***    Name - Name of Location; icp(i) - No. of the Control point (CP);
c***    icp1 - No. of points u/s of CP, icp2 - All Points u/s of CP;
      do 17 i = 1, nloc
       read(1,2) name(i)
2      format(/a)
       read(1,*) icp(i), icp1(i), (icp2(i,j),j=1,icp1(i))
       write(2,3) icp(i), name(i)
       write(*,3) icp(i), name(i)
3      format(/10x,'Location No.'i3', ',a/)
       if(icp1(i).gt.0) Write(2,5) (icp2(i,j),j=1,icp1(i))
5      format(' Upstream Location(s) ='5i4)

c***    smax - Max. storage capacity (m3); smin - Dead storage (m3);
c***    stor(1) - Starting storage, nn - Points in EAC Table; nn(i) = 0
c***    for non-reservoir locations;
c***    gfac = 0.1:1 for storage dam, = 2 for ungated dam, = 3 for diversion

       read(1,*) smax(i), smin(i), stor(i,1), nn(i), gfac(i)
       write(*,'(''  Stor OK  ''$)')
c***  chcp = Safe capacity of d/s channel (cumec), rcl = reservoir critical
c***  level (m), cfi = critical flood inflow (cumec), rinc = maximum
c***  permissible change in release in consequtive periods as fraction
       if(gfac(i).le.1) read(1,*) frl(i), chcp(i), rcl(i), cfi(i)
     1    , rinc(i)
       write(2,6) smax(i), smin(i), stor(i,1)
6      format(' Max. Storage    ='e10.3' Cubic m,'/' Dead Storage    '
     1    '='E10.3' Cubic m,'/' Initial Storage ='e10.3' Cubic m')

       if(gfac(i).le.1) write(2,7) frl(i), chcp(i), rcl(i), cfi(i)
     1    , rinc(i)
7      format(' Full Res. Level ='f10.3' m'/' Safe capacity of d/s'
     1    ' channel ='f8.0' cumecs'/' Reservoir critical level ='
     2    f8.3' m'/' Critical flood inflow ='f8.1' cumec'/' Release in '
     3    'consequtive periods can not change by more than'f5.2' times')
       if(gfac(i).eq.2) write(2,*)
     1     'This dam is ungated, reservoir routing will be performed'
       if(gfac(i).eq.3) write(2,*) ' This is a diversion structure'
       if(gfac(i).eq.3) nn(i) = 0

c***  elev - elevation; area - area at corresponding elevation (M Sqm);
c***    cap - capacity at corresponding elevation (M Cum);
```

```
c***  Relc - spillway release capacity (cumec)

        if(nn(i).gt.0) then
          do j = 1, nn(i)
           read(1,*) elev(i,j), area(i,j), cap(i,j), relc(i,j)
          enddo
          write(*,'('' EAC-Table  OK    '',$)')
        endif

c***    Data related to local flows calculation, demands and rule levels
c***    INFL =1: inflows (cumec) are input; =2: computed using other LOC data
c***    FAC - Inflows read (local or at LOC j) will be multiplied by this;
c***    inod - Id. of location whose inflow data is to be used to
c***    estimate inflow at present structure.
c***    amflo - Min release to be made in Mm3; rule - upper rule levels
c***    evpd - evaporation depth in m/month;
c***   irout = 0 - no routing, =1 - release to be routed to d/s dam

        read(1,*) infl, fac(i), amflo(i), irout(i), idp(i)
        if(infl.eq.1) write(2,13) fac(i)
 13     format(' Inflows read will be multiplied by ='f9.2)
        write(*,'(''   irout OK    '',$)')
        if(nn(i).gt.0) then
          if(gfac(i).le.1) read(1,*) (rule(i,j),j=1,12)
          if(gfac(i).eq.2) call rrl(i)               ! Ungated dam, res. routing
          if(gfac(i).le.2) read(1,*) (evpd(i,j),j=1,12)
          write(*,'('' Evpd  OK    '',$)')
        endif
        if(irout(i).eq.1) then
         write(2,*) 'Muskingum method of routing will be used'
         read(1,*) imeth(i)     ! routing method
         if(imeth(i).eq.1) read(1,*) ak(i), ax(i)       ! Musk method - k,x
         call routin(i)   ! set routing parameters
        endif

c***    Local flows
        if(infl.eq.1) then
          read(1,*) (flow(i,j), j = 1, nmon)
          do j = 1, nmon
           flow(i,j) = flow(i,j) * fac(i)
          enddo
         else
          read(1,*) inod
          write(2,15) i, inod, fac(i)
 15       format(' Flow at node'i3' = Flow at node'i3' *'f5.2)
          do j = 1, nmon
           flow(i,j) = flow(inod,j) * fac(i)
          enddo
         endif
         write(*,'(''  Flow  OK'')')
 17     continue

c***   End of Input block
```

Listing of Sample Input File

```
Flood Control Operation of a System

  4  6  5  7  10  1.   nloc  ih0, id0, im0, nmon, dt

  Reservoir 1 with gated spillway

  1  0  0  0

  1420.E+06  20.E+06  800.0E+06  14  0.9  Smax/Smin/Stor(1)/nn/gfac
  189.59 15000.0 193.5 17000.0  1.7       FRL/chcp/rcl/cfi/rinc

  163.07        0.195E+06       0.024E+06          0.00
  166.12        3.159E+06       4.890E+06          0.00
  170.69        8.043E+06      29.078E+06          0.00
  176.78       18.525E+06     103.203E+06          0.00
  179.83       32.189E+06     180.844E+06        279.23
  182.88       50.640E+06     304.596E+06       2704.73
  185.93       73.358E+06     497.225E+06       6718.83
  188.98      100.133E+06     763.135E+06      12022.37
  189.59      105.621E+06     829.415E+06      13225.70
  190.50      113.314E+06     926.847E+06      15095.94
  192.02      125.047E+06    1108.144E+06      18427.08
  193.55      137.673E+06    1309.163E+06      21982.90
  194.00      142.000E+06    1420.000E+06      23400.00
  194.50      148.700E+06    1507.000E+06      24900.00

  1  10.0   100   1  1                  infl   fac mflo  rout  dp

  188.75  188.25  187.75  187.25  186.75  188.75  189.25  189.59  189.59
189.59
  189.59  189.25  UPPER RULE CURVE

  0.1402  0.1402  0.1890  0.2408  0.3048  0.2164  0.1524  0.1524  0.1524
0.1524
  0.1524  0.1524  EVAP_DEPTH

  1       Routing method
   4.0  0.1                             Musk K and X

   566.41   638.49   710.56   782.64   854.72  1040.78  1226.85  1412.91
  1598.98  1827.74  2056.50  2285.26  2514.02  2745.04  2976.07  3207.09

  Reservoir 2

  2  1  1

 3657.489E+06  740.018E+06  3000.0E+06  9  0.9
 420.0  9000.0  422.0  14000.0   1.6

    402.336        33.7481E+06        295.2354E+06    0.0
    403.550        42.3247E+06        740.0178E+06   10.0
    408.432        77.1263E+06       1205.4404E+06  100.0
    411.480       113.2015E+06       1450.5711E+06  900.0
```

```
   414.528        153.5700E+06       1949.4692E+06 1500.0
   417.576        194.3948E+06       2478.7512E+06 3000.0
   420.624        236.8414E+06       3138.7994E+06 5000.0
   422.760        272.9351E+06       3657.4890E+06 7000.0
   423.000        278.0000E+06       3766.2700E+06 9500.0

 1  5.0  100.0  1  1

 419.50  418.00  416.50  415.00  413.00  415.00  418.00  422.50  422.76
422.76
 422.00  420.50   UPPER RULE CURVE

 0.0682   0.07  0.1271   0.177  0.2387  0.198  0.1426  0.1147  0.099
0.1085
 0.078  0.0682  EVAP_DEPTH

 1      routing method
 4.0  0.1      musk k & x
       35.63     98.66  1307.07  1164.30   355.60      51.70     31.60
 14.86       9.93       6.43       3.10       0.81     116.30    2023.00
3745.08   2068.22    224.45      63.76     34.61

 Reservoir 3 with ungated spillway

 3  1  2  0

 829.415E+06    89.941E+06  200.737E+06  12  2

     170.69      8.043      29.078e+06       0.00
     173.74     11.929      58.898e+06       0.00
     176.78     18.525     103.203e+06       0.00
     179.83     32.189     180.844e+06     279.23
     182.88     50.640     304.596e+06    2704.73
     185.93     73.358     497.225e+06    6718.83
     188.98    100.133     763.135e+06   12022.37
     189.59    105.621     829.415e+06   13225.70
     190.50    113.314     926.847e+06   15095.94
     192.02    125.047    1108.144e+06   18427.08
     193.55    137.673    1309.163e+06   21982.90
     194.00    142.000    1420.000e+06   23400.00

 1  10  500.0  0   1
 0.0682    0.07  0.1271   0.177  0.2387  0.198  0.1426  0.1147  0.099
0.1085
 0.078  0.0682  EVAP_DEPTH

 13.54  333.79  172.37  263.22   45.29   12.31   14.30
 0.47    0.89    0.86    0.50    0.27    0.46  229.22  630.41   21.94
5.99    2.66    1.77

 Location 4 -- Diversion

 4  2  2  3

 12.5E+05  3.5E+05   6.5E+05  0  3

 1  10.0  500.0  0  1

 6.48   4.26   3.80  12.83   4.82   0.00   0.00
 0.00   0.00   0.00   0.00   0.00 145.33  50.68   5.29   3.11.  0.00   0.00
```

Listing of Sample Output File

```
Flood Control Operation of a System

 Time-step size for simulation =  1. Hr

          Location No.  1,     Reservoir 1 with gated spillway

 Max. Storage      =  .142E+10 Cubic m,
 Dead Storage      =  .200E+08 Cubic m,
 Initial Storage =  .800E+09 Cubic m
 Full Res. Level =   189.590 m
 Safe capacity of d/s channel =  15000. cumecs
 Reservoir critical level = 193.500 m
 Critical flood inflow = 17000.0 cumec
 Release in consequtive periods can not change by more than 1.70 times
 Inflows read will be multiplied by =    10.00
 Muskingum method of routing will be used

 Muskingum parameters for reach below  1 :    .024    .220    .756

          Location No.  2,     Reservoir 2

 Upstream Location(s) =   1
 Max. Storage      =  .366E+10 Cubic m,
 Dead Storage      =  .740E+09 Cubic m,
 Initial Storage =  .300E+10 Cubic m
 Full Res. Level =   420.000 m
 Safe capacity of d/s channel =   9000. cumecs
 Reservoir critical level = 422.000 m
 Critical flood inflow = 14000.0 cumec
 Release in consequtive periods can not change by more than 1.60 times
 Inflows read will be multiplied by =     5.00
 Muskingum method of routing will be used

 Muskingum parameters for reach below  2 :    .024    .220    .756

          Location No.  3,     Reservoir 3 with ungated spillway

 Upstream Location(s) =   2
 Max. Storage      =  .829E+09 Cubic m,
 Dead Storage      =  .899E+08 Cubic m,
 Initial Storage =  .201E+09 Cubic m
  This dam is ungated, reservoir routing will be performed
 Inflows read will be multiplied by =    10.00

          Location No.  4,     Location 4 -- Diversion

 Upstream Location(s) =   2   3
 Max. Storage      =  .125E+07 Cubic m,
 Dead Storage      =  .350E+06 Cubic m,
 Initial Storage =  .650E+06 Cubic m
  This is a diversion structure
 Inflows read will be multiplied by =    10.00


 System Operation Simulated for 10 Periods, Beginning (MM DD HH) 07 05 05
```

RESULTS FOR LOCATION NO. 1 - Reservoir 1 with gated spillway

Mn-DD-Hr	Init_Sto m m3	Init_lev m m3	Loc_flo m3/s	US_flo m3/s	Evap m m3	Tot_Rel m3/s	End_sto m m3	End_lev m	Case
7-05-06	800.00	189.319	5664.	.0	.0	100.0	820.01	189.503	RuFr
7-05-07	820.01	189.503	6385.	.0	.0	100.0	842.61	189.713	RuFr
7-05-08	842.61	189.713	7106.	.0	.0	170.0	867.56	189.946	FrI+
7-05-09	867.56	189.946	7826.	.0	.0	289.0	894.67	190.199	FrI+
7-05-10	894.67	190.199	8547.	.0	.0	491.3	923.65	190.470	FrI+
7-05-11	923.65	190.470	10408.	.0	.0	835.2	958.09	190.762	FrI+
7-05-12	958.09	190.762	12269.	.0	.0	1419.9	997.12	191.089	FrI+
7-05-13	997.12	191.089	14129.	.0	.0	2413.8	1039.27	191.443	FrI+
7-05-14	1039.27	191.443	15990.	.0	.0	4103.4	1082.04	191.801	FrI+
7-05-15	1082.04	191.801	18277.	.0	.0	6975.8	1122.70	192.131	EmI+

RESULTS FOR LOCATION NO. 2 - Reservoir 2

Upstream Location(s) = 1

Mn-DD-Hr	Init_Sto m m3	Init_lev m m3	Loc_flo m3/s	US_flo m3/s	Evap m m3	Tot_Rel m3/s	End_sto m m3	End_lev m	Case
7-05-06	3000.00	419.983	178.	2.4	.0	100.0	3000.25	419.984	RuFr
7-05-07	3000.25	419.984	493.	26.2	.0	100.0	3001.71	419.991	RuFr
7-05-08	3001.71	419.991	6535.	45.9	.0	100.0	3025.00	420.098	RuFr
7-05-09	3025.00	420.098	5822.	79.1	.0	160.0	3045.62	420.194	FrI+
7-05-10	3045.62	420.194	1778.	135.2	.0	256.0	3051.55	420.221	FrI+
7-05-11	3051.55	420.221	259.	230.5	.0	409.6	3051.79	420.222	FrI+
7-05-12	3051.79	420.222	158.	392.2	.0	655.4	3051.36	420.220	FrI+
7-05-13	3051.36	420.220	74.	667.1	.0	1048.6	3050.21	420.215	FrI+
7-05-14	3050.21	420.215	50.	1134.3	.0	1677.7	3048.39	420.207	FrI+
7-05-15	3048.39	420.207	32.	1928.5	.0	2684.4	3045.74	420.194	FrI+

RESULTS FOR LOCATION NO. 3 - Reservoir 3 with ungated spillway

Upstream Location(s) = 2
Ungated dam -- Reservoir Routing by Modified Puls Method

Beginning Elevation = 180.320 m

Mn-DD-Hr	Init_Sto m m3	Loc_flo m3/s	US_flo m3/s	Evap m m3	Release m3/s	End_sto m m3	End_lev m
7-05-06	200.74	135.	2.	.0	632.9	198.9	180.275
7-05-07	198.89	3338.	26.	.0	819.1	208.4	180.509
7-05-08	208.39	1724.	44.	.0	883.7	211.7	180.590
7-05-09	211.69	2632.	59.	.0	1006.9	218.0	180.745
7-05-10	217.97	453.	86.	.0	975.1	216.3	180.705
7-05-11	216.35	123.	131.	.0	925.9	213.8	180.643
7-05-12	213.84	143.	205.	.0	886.6	211.8	180.594
7-05-13	211.83	5.	325.	.0	848.6	209.9	180.546
7-05-14	209.89	9.	517.	.0	826.6	208.8	180.518
7-05-15	208.77	9.	824.	.0	827.0	208.8	180.519

RESULTS FOR LOCATION NO. 4 - Location 4 -- Diversion

Upstream Location(s) = 2 3

Mn-DD-Hr	Init_Sto m m3	Loc_flo m3/s	US_flo m3/s	Diversion m3/s	Release m3/s	End_sto m m3
7-05-06	.65	64.800	635.	500.	33.49	1.25
7-05-07	1.25	42.600	845.	500.	387.90	1.25
7-05-08	1.25	38.000	928.	500.	465.96	1.25
7-05-09	1.25	128.300	1066.	500.	694.53	1.25
7-05-10	1.25	48.200	1061.	500.	609.45	1.25
7-05-11	1.25	.000	1057.	500.	557.30	1.25
7-05-12	1.25	.000	1092.	500.	591.78	1.25
7-05-13	1.25	.000	1173.	500.	673.18	1.25
7-05-14	1.25	.000	1343.	500.	843.08	1.25
7-05-15	1.25	.000	1651.	500.	1151.29	1.25

Study Group

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