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REAL – TIME RESERVOIR OPERATION - A REVIEW

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PREFACE

India is bestowed with rich water resources but more than 80 % of the rainfall over this country falls in four monsoon months from June to September. Because of high time and spatial variability of rainfall, a number of dams have been constructed all over the country to tap the available water resources so that this water can be utilised in accordance with the requirements of mankind.

For the efficient use of water resources, proper management of the reservoirs is required. Reservoir operation forms a very important part in planning and management of water resources system. After a dam has got constructed, detailed guidelines in the form of "Reservoir operation policy" will have to be given to the operator for enabling him to take decisions about storing or releasing water.

Increasing population, urbanisation and deforestation have increased not only the demand for water supply but also the damage potential arising from floods. For the better management of existing reservoirs, real-time operation is employed. "Real-Time operation" is the operation of the reservoir concurrently with a computer system such that the results of the computation are available well in time to usefully influence or control the operation. Real-time operation is especially suitable during floods where the system response changes very fast and decisions have to be taken quickly and adopted frequently.

The present report deals with the various aspects of real-time reservoir operation including its needs, logistic requirements, special considerations and advantages. The different real-time operation studies have also been discussed. The report has been prepared by Sh. M.K. Goel, Sc. "B" and Sh. P.K. Agarwal, RA under the guidance of Dr. S.K. Jain, Sc. "E" of WRS Division.

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ABSTRACT

Multipurpose reservoir projects with the objectives of conservation of water and flood control are quite common. The conservation purposes, which include irrigation, hydroelectric power generation, municipal and industrial water supply, navigation and recreation etc. require that water should be stored in the reservoir during the periods when the inflows exceed the demand and should be released from the storage when situation reverses. The flood control purpose requires empty storage space in the reservoir so that the incoming floods can be absorbed and moderated to permissible limits. This conflict between the two purposes in terms of storage space requirements is resolved through proper operation of reservoirs. A reservoir operation policy specifies the amount of water to be released from the storage at any time depending upon the state of the reservoir, level of demands and any information about the likely inflow in the reservoir.

The term "Real-Time" operation is used to denote that mode of operation in which the control decisions for a finite future time horizon are taken based on the condition of the system at that instant of time when this decision is to be taken and the forecasts about the likely inputs over this time horizon. Optimization is one of the most powerful and popular technique for solving various problems associated with the operation of a reservoir. During the past few years, its use has grown tremendously, due to wider availability of computer

and efficient general purpose packages.

In the present report a comprehensive review of literature pertaining to reservoir operation in real-time mode has been made. Telemetry system and real-time flow forecasting which are essential prerequisites for real-time reservoir operation have been discussed. A comprehensive bibliography is given at the end for reference purposes.

INTRODUCTION

1.0 THE NEED FOR RESERVOIRS

Among the various components of a water resources development project, reservoirs are the most important. A reservoir is created by constructing dam across a stream. Principal function of a reservoir is regulation of natural streamflow by storing surplus water in a rainy season and releasing the stored water in a future dry season to supplement the reduction in riverflow. In short, the purpose of a reservoir is to equalize the natural streamflow and to change the temporal and spatial availability of water. The water stored in a reservoir may be diverted to far away places by means of pipes or canals resulting in spatial changes or it may be stored in the reservoir and released later for beneficial uses giving rise to temporal changes.

Depending upon the magnitude of natural inflows and demands at a particular time, water is either stored in the reservoir or supplied from the storage. As a result of storing water, a reservoir provides head of water which can be used for generation of electric power. In case of flood control projects, it provides empty space for storage of water thereby attenuating the hydrograph peaks. A reservoir also provides pool for navigation to negotiate rapids, habitat for aqua life and facilities for recreation and sports. It enhances scenic beauty, promotes afforestation and wild life.

Depending upon the number of purposes which a reservoir is to serve, a reservoir may be classified either as a single purpose reservoir or as a multipurpose reservoir. A single purpose reservoir is constructed to serve only one purpose. The purposes may be either of conservation purposes such as water supply for irrigation, navigation, municipal and industrial needs, generation of hydroelectric power or flood control. A multipurpose reservoir is developed to satisfy more than one purpose. The purposes may be a combination of flood control, irrigation, municipal and industrial water supply, hydroelectric power generation and navigation.

1.1 RESERVOIR OPERATION PROBLEM

Once the structured facilities like dams, barrages, hydropower plants, which are required for utilization of water resources come into being, the benefits that could be reaped depend to a large extent upon how these facilities are managed. Thus the efficient use of water resources requires not only judicious design but also proper management after construction.

Reservoir operation forms a very important part of planning and management of water resources system. Once a reservoir has been developed, detailed guidelines have to be given to the operator which enable him to take decisions about storing or releasing water.

The climate experienced in Indian subcontinent is of monsoon type in which most of the water is received during the monsoon period from June to September. The reservoirs are commonly built in India for conservation and flood control purposes. The conservation demands are best served when the reservoir is as much full as possible at the end of the filling period. The flood control purpose, on the other hand, requires empty storage space so that the incoming floods can be absorbed and moderated to permissible limits. The conflict between the two purposes in terms of storage space requirements is resolved through proper operation of reservoirs.

A reservoir operation policy specifies the amount of water to be released from the storage at any time depending upon the state of the reservoir, level of demands and any information about the likely inflow in the reservoir. A single purpose reservoir is constructed to serve only one purpose. The operation problem for such reservoir is to decide about the releases to be made from the reservoir so that the benefits for that purpose are maximized. For a multipurpose reservoir, in addition to the above, it is also required to optimally allocate the release among several purposes.

1.2 CHARACTERISTICS AND REQUIREMENTS OF WATER USES

The complexity of the problem of reservoir operation depends upon the extent to which the various purposes which a reservoir is supposed to serve are compatible. If the purposes are relatively more compatible, comparatively less effort is needed for coordination. The requirements of different purposes are explained below:

(a) Irrigation

The irrigation requirements show a highly seasonal variation and the variation largely depends upon the cropping patterns in the command area. The irrigation demands are consumptive in nature and only a small fraction of the supplied water is available to the system as return flow. These requirements have direct correlation with the rainfall in the command area. The safety against drought depends upon the storage available in the reservoir and hence it is desirable to maintain as much reserve water in storage as possible consistent with the current demands.

(b) Hydroelectric power

The hydroelectric power demands usually vary seasonally and to a lesser extent daily and hourly too. The degree of fluctuation depends upon the type of loads being served, viz. industrial, municipal and agricultural. Hydroelectric power demand comes under non consumptive use of water.

(c) Municipal and industrial water supply

Generally, the water requirements for municipal and industrial purposes are quite constant throughout the year, more so when compared with the requirements for irrigation and hydroelectric power. The water requirements increase from year to year due to growth and expansion. The seasonal demand peak is observed in summer. The supply system for such purposes is designed for very high level of reliability.

(d) Flood control

Flood control reservoirs are designed to moderate the flood flows that enter the reservoirs. The flood moderation is achieved by storing a fraction of inflows in the reservoir and releasing the balance water. The degree of moderation or flood attenuation depends upon the empty storage space available in the reservoir when the flood impinges it. As far as possible, the releases from the storage are kept less than the safe capacity of downstream channel.

(e) Navigation

Many times storage reservoirs are designed to make a stretch of river issuing from the reservoir navigable by maintaining sufficient flow depth in the stretch of river channel used for navigation. The water requirements for navigation show a marked seasonal variation. The demand during any period also depends upon the type and volume of traffic in the navigable waterways.

(f) Recreation

The benefits from this aspect of reservoir are derived when the reservoir is used for swimming, boating, fishing and other water sports and picnic. Usually the recreation benefits are incidental to other uses of the reservoir and rarely a reservoir is operated for recreation purposes. Large and rapid fluctuations in water level of a reservoir are deterrent to recreation.

1.3 CONFLICTS IN RESERVOIR OPERATION

While operating a reservoir which serves more than one purpose, a number of conflicts arise among demands of various purposes. The conflicts which arise in multipurpose reservoir operation may be classified as:

(a) Conflicts in space

These type of conflicts occur when a reservoir (of limited storage) is required to satisfy divergent purposes, for example, water conservation and flood control. If the geological and topographic features of the dam site and the funds available for the project permit, a dam of sufficient height can be built and storage space can be clearly allocated for each purpose. In case of reservoirs with seasonal storage, flood control space can be kept empty to moderate the incoming floods and the conservation pool can be operated after the filling season to meet the conservation demands. However, this essentially amounts to saying that a multipurpose reservoir is a combination of several single purpose reservoirs.

(b) Conflicts in time

The temporal conflicts in reservoir operation occur when the use pattern of water varies with the purpose. The conflicts arise because release for one purpose does not agree with the other purpose. For example, irrigation demands may show one pattern of variation depending upon the crops, season and rainfall while the hydroelectric power demands may have a different variation. In such situations, the aim of deriving an operating policy is to optimally resolve these conflicts.

(c) Conflicts in discharge

The conflicts in daily discharge are experienced for a reservoir which serve for more than one purposes. In case of a reservoir serving for consumptive use and hydroelectric power generation, the releases for the two purposes may vary considerably in the span of one day. Many times a small conservation pool is created on the river downstream of the powerhouse which is used to damp the oscillations in the powerhouse releases.

1.4 CONVENTIONAL RESERVOIR OPERATION POLICY

A reservoir is operated according to a set of rules or guidelines for storing and releasing water depending upon the purposes it is required to serve. The decisions are made releases in different time periods in accordance with the demands.

For reservoirs which are designed for multiannual storage, the operation policy is based on long term targets. The estimates of water availability are made using long term data. The demand for conservation uses like irrigation, water supply, navigation and hydroelectric power are worked out by projecting the demand figures. If hydroelectric power generation is not one of the purposes of the reservoir, water is allocated among various consumptive uses. The extent of water releases for variety of uses which can be served from storage in the reservoir on long term basis are determined and the reservoir is operated accordingly. In the period of drought, based on prespecified priorities, the supply for some uses is curtailed keeping in view bare minimum demands of each purpose. Consideration is given to the maintenance of essential services even if it is at the cost of agriculture and industrial production. If generation of power is one of the purposes of the reservoir, then releases for consumptive uses are routed through the power house to generate the required energy.

The operating policy of reservoirs designed and operated for seasonal storage is based on yearly operation. Reservoir operation study is carried out for long term record taking into account the demand estimates for various conservation uses. Policy decisions are arrived at introducing the concepts of reliability. In a country like India, where most of the rainfall is concentrated in monsoon months, water demands can generally be met during the monsoon period. For meeting water demands during non-monsoon months, a fair idea of the water availability is required and the reservoir operation for the year is planned on the basis of earlier decided policy. If necessary, allocation for some purposes can be curtailed, based on priority. In multipurpose storage reservoirs located in the regions where floods can be experienced at any time of the year and flood control is one of the main purposes, permanent allocation of the space exclusively for flood control at the top of conservation pool becomes necessary. Flood control space is always kept reserved although the space may vary 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 and that even when a maximum probable flood is likely to occur, its peak will be substantially reduced and flood damage on the downstream would not exceed permissible limits. In reservoirs in regions where floods are experienced only in a particular season or period of the year, seasonal allocation of space is made for flood control during different periods of flood season depending upon the magnitude of floods likely to occur in given period and the space is thereafter utilized for storing inflows for conservation uses.

1.4.1 Standard Linear Operating Policy

The simplest of the reservoir operation policies is the standard linear operating policy (SLOP). According to this policy, if the amount of water available in storage is less than the target release, whatever quantity is available is released. If availability is more than target, then a release equal to the target is made as long as storage space is available to store excess water and thereafter,all the water in excess of maximum storage capacity is released. This policy is graphically represented in Figure 1.1.

The SLOP is a one time operation policy without relation to the release of water at any other time. This type of time isolated releases of water is neither beneficial nor desirable. The water beyond the target output in any period

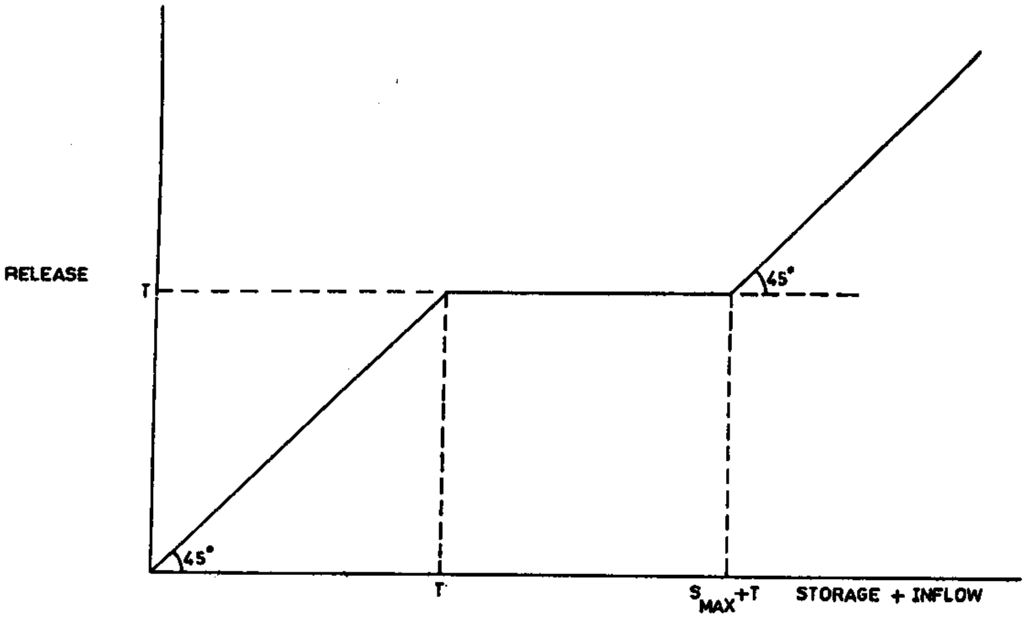

Fig 1.1 STANDARD LINEAR OPERATING POLICY

has no economic value. This policy is not used in day-to-day operation due to its rigidness and above drawbacks. It is however, extensively used in planning studies.

1.4.2 Rule Curves

One type of management frequently used for reservoir operation with flood control as one of the purpose is based on rule curves. A rule curve or rule level specifies the empty space to be maintained in a reservoir during different times of the year. Here the implicit assumption is that a reservoir can best satisfy its purpose if the empty space specified by the rule curve are maintained in the reservoir at different times. The rule curve as such does not give the amount of water to be released from the reservoir.

1.4.3 Concept Of Storage Zoning

In this concept, the entire reservoir storage region is conceptually divided in a number of zones by drawing imaginary horizontal planes. The zoning of reservoirs and the rules governing the maintenance of storage levels in a specified range are based upon the conviction that at a specified time, an ideal storage zone exists for a reservoir which, when maintained, gives the maximum expected benefits. This concept is in some way akin to concept of rule curve. Only added advantage here is that this approach gives more freedom to the decision maker to vary the level within the specified zone. Typically the various storage zones are:

(i) **Dead storage zone:** Also called inactive zone, the space in this zone is normally meant to absorb some of the sediment entering the reservoir or to provide minimum head for hydropower plants. The water in this zone may be utilized only under extreme dry conditions. This is the lowest zone of a reservoir.

(ii) **Buffer zone:** This is the storage space on the top of dead storage zone and the reservoir level is brought down to this zone under extreme drought situations. When the reservoir is in this zone, the release from the reservoirs caters only to essential needs.

(iii) **Conservation zone:** This is the zone in which the water is stored to satisfy the demands for various conservation purposes like hydropower, irrigation and water supply etc. This zone provides the bulk of the storage space in reservoirs designed for conservation purposes.

(iv) **Flood control zone:** This is the storage space exclusively earmarked for absorbing floods during high flood periods. This zone is located on top of conservation zone. The releases are increased as necessary when the water stored in the reservoir falls in this zone.

(v) **Spill zone:** This storage space above the flood control zone corresponds to the flood rise during extreme floods and spilling. This space is occupied mostly during high flows and the releases are at or near maximum.

A graphical representation of the various zones is given in fig. 1.2.

The normal operation policy is to release as much as possible when the reservoir is in the spill zone, to release as much as possible without causing flood damages downstream when the reservoir content is in flood control zone, and to bring the reservoir to the top of the conservation zone at the earliest possible time. The release from the conservation zone is governed by the requirements of water for various purposes intended to be met by the stored water and the day to day releases may be adjusted based on the inflow anticipated and the future requirements up to the end of the operating horizons. When the amount of water is anticipated to be short compared to the demand, releases may be curtailed. The limits of various zones may vary with time.

1.5 SYSTEM ENGINEERING TECHNIQUES

System engineering is concerned with decision making for those systems on which some controls can be applied to best obtain the given objective subject to various social, political, financial and other constraints. A number of system engineering techniques are available for solving various problems associated with reservoir operation. Among them, two techniques which are most commonly used are simulation and optimization.

(a) Simulation

Simulation is the process of designing a computerized model of a system and conducting experiments with it for

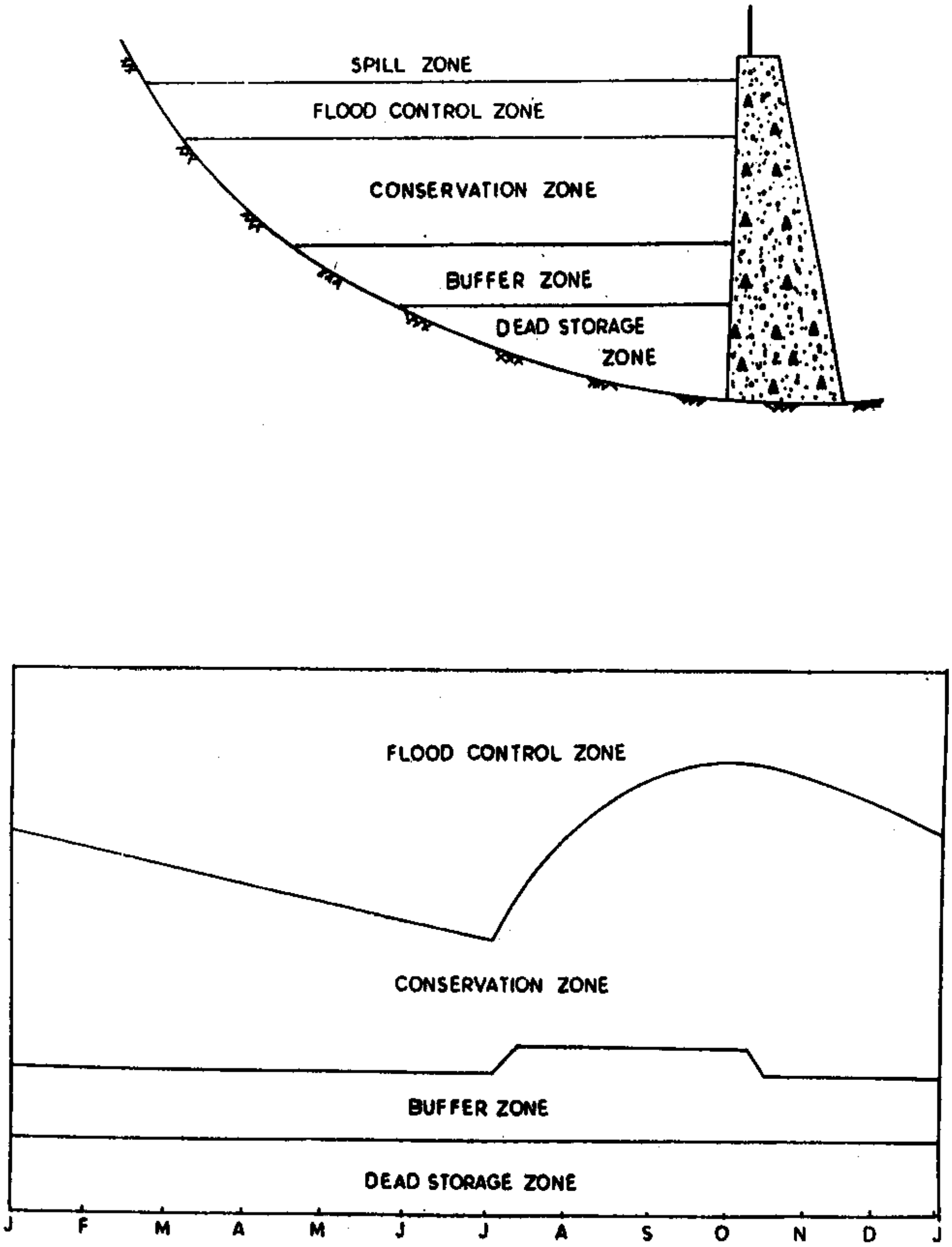

FIGURE 1-2- SCHEMATIC REPRESENTATION OF VARIOUS RESERVOIR ZONES understanding the behaviour of the system and for evaluating various strategies for its operation. The essence of simulation is to reproduce the behaviour of the system. It allows for controlled experimentation on the problem without causing any disturbance to the real system. However, simulation analysis does not yield an immediate optimal answer and require a number of iterations to arrive at the optimum solution.

(b) Optimization

Optimization is the science of choosing the best solution from a number of possible alternatives. Optimization methods find out a set of decision variables such that the objective function is optimized. The complexity of optimization problems depends upon the number of factors affecting a particular choice. Two most commonly used techniques for reservoir operation are linear programming and dynamic programming.

In linear programming, the objective functions and constraints are linear. Optimum solution can be reached graphically or algebraically using simplex method. It also provides economic interpretation of the problem and carries out sensitivity analysis.

Dynamic programming is an optimization technique based on multistage decision process in which the decisions are taken in stages. It is an enumerating technique based on the Bellman's principle of optimality. It can be applied to linear as well as nonlinear objective functions and constraints.

REAL-TIME RESERVOIR OPERATION

2.0 NEED FOR REAL-TIME RESERVOIR OPERATION

Urbanization has increased not only the demand for water supply but also the damage potential arising from floods. The reservoirs provide an effective means to satisfy the water demand and reduce the flood damage. In recent years, it has become difficult to construct new reservoirs because of social and environmental ramifications. Under these circumstances, the problem of efficient utilization of existing reservoirs has become more important.

Generally, the operation of reservoir system is based on fixed operation rules. These rules are developed taking into account the demands of the past and using data from historical or synthetic time series of hydrological variables. But the probability is very small that an actual event will occur in the same way as prior events of the same type. A reservoir system for an actual event can be operated efficiently if the time interval between the occurrence of the event and the execution of the control adapted for this event is short. To react for the current situation and to take into account the variability of inflows into the reservoir system, the real-time operation models are being developed. In real-time operation, decisions regarding releases are made relatively quickly and are based on short term information. The definition of the short term varies in accordance with the purpose of the reservoir. If the reservoir is operated for flood control purpose, then short term may be confined to daily or even hourly operation and if the system is mainly for irrigation purpose, then the short term may be a week or a month.

The term "Real-time" reservoir operation is used to denote that mode of operation in which the control decisions for a finite future time horizon are taken based on the condition of the system at that instant of time when these decisions are to be taken and the forecast about the likely inputs over this time horizon. The forecast of inflows is made using either the information about the rainfall in the catchment or measured discharge at an upstream station and based on this, a control decision is taken. After a known time interval, forecasts are updated and the control decisions are modified in light of these. Optimal real-time operation of reservoir system requires the "best" reservoir releases to satisfy various long term system purposes and short term limitations on operation due to physical constraints while using forecast information.

For existing reservoirs, better management means better reservoir yield and greater flood protection through improved operation policy rather than future expansion. The operation policy for the reservoir may be daily, weekly or monthly depending upon the main goals of the reservoir. Accordingly, the streamflow forecast will have to be daily, weekly or monthly. Most of the real-time models are developed for short interval forecasting. The models are continuously updated with each bit of new information.

Real-time operation is especially suitable during floods where the system response changes very fast and decisions have to be taken quickly and adapted frequently. First of all, an optimization model of the system is developed. The release from the reservoir is taken as decision variable. A forecasting algorithm is used to provide inflow forecast for a finite number of future time periods based upon the present status of the system as well as its past behaviour. Now using the information about the state of the system and forecast of inflows, the optimization model is used to determine the optimum quantity of water to be released from the reservoir so that the objective function is optimized. Although the optimum releases are determined for finite number of future time periods, they are implemented only for one immediately next period. After this period the next set of observations becomes available which is used to update the information about the state of the system. This entire process is repeated after end of each time interval.

2.1 LOGISTIC REQUIREMENTS FOR REAL-TIME OPERATION

A successful application of the real-time operation procedure requires a good telemetry system through which data can be observed on-line. The term "on-line" implies that the data are collected, transmitted and fed to a model and the model's output is obtained and then used in one uninterrupted sequence of activities. By the increasing prevalence of high capability but low cost process control computers connected with telemetry networks and remote control features, the technical support for the real-time operation today is realizable. Controls in real-time operation can be executed successfully if

- sufficient measurement of the actual hydrometeorological data (rainfall, discharge, reservoir contents) and the specification of demands are possible.
- model for the evaluation of discharge forecasts based on the measured data and models for the optimization of the reservoir control based on the discharge forecasts are available and can be executed in sufficient short time.

2.1.1 Real-Time Hydrological Forecasting

Hydrological forecasting is one of the most important aspects of applied hydrology. The hydrological forecasting helps in rational regulation of runoff, utilization of water resources in hydropower generation, inland navigation, irrigation, drinking and industrial water supply. They are also gainfully utilized for advance flood warnings.

The use of hydrologic forecasting in operation of reservoirs can make the reservoirs more efficient in achieving the purposes for which these are designed. The main components involved in the inflow forecasting are weather forecasting if possible, rainfall runoff modeling and channel routing. For a forecast in proper time, the transmission of information and processing of data has to be done very quickly. This is possible only with the help of a computer.

The forecasting can be classified in two categories: long term forecasting and short term forecasting. The long term forecasting is usually aimed towards generation of random events which preserve, to a certain extent, the statistical behavior of historical data. The variables used in this type of forecasting are aggregate parameters like monthly discharges, weekly rainfalls and so on. On the other hand short term forecasting is done in real-time and the processing is done at the same time when the events take place. The forecasts are also continuously updated using observed values of the variables at discrete times. The interest is not only in the statistical behaviour of the variable but in the absolute value of forecasting variable. It has been revealed by a number of studies that benefits from real-time operation of a reservoir can be substantially increased if good forecasts are available.

Real-time flood forecasting involves the estimation of flood discharges or water levels in a river some period prior to it's occurrence. The forecast lead time proves useful in mitigating some of the adverse effects of flooding. The forecast lead time is a characteristic of the catchment and may be due to (1) the time taken by the catchment to transform the rainfall into the run-off output at a point or (2) time taken by the flood wave to move from one point to another point in the river without any intermediate contributions. For these two cases, forecasts are formulated using different categories of mathematical models. Rainfall- runoff models are used for case (1), whereas flood routing models are used for case(2). More often, modeling of a catchment, except headwater areas, requires use of rainfall runoff relations in combination with routing relations. Therefore, for such areas, only those models are considered which can deal with these two aspects in combination.

The time interval at which a reservoir is to be controlled depends on the purpose of control. If the operation is for flood control during months of high flows, the operation decision may be taken and updated at very short intervals such as a day or even several hours. For other purposes, a larger interval may be more practical.

The need for on-line control arises where the response of the system to the application of control is quick and any delay in taking a decision is likely to result in significant losses. This requirement comes during the operation of a reservoir for flood control where the decisions have to be implemented, evaluated and modified in quick succession. The gain from on-line operation can be substantially increased if good algorithm giving reliable forecast of the inputs to the system is available.

A number of models are available for forecasting of streamflow. Some of these are SSARR (Streamflow Synthesis and Reservoir Regulation) model, US Bureau API type models, HEC-IF, Stanford Watershed model, and the NAM model.

2.1.2 Telemetry System

The exchange of information between widely separated data collection centres and forecasting centre, and recording of instantaneous values of continually changing operational quantities at a far away point is called telemetry. Real-time hydrological forecasting depends to a large extent, on the availability of hydrometeorological data at the forecasting station. A sophisticated hydrological model and a fast computer system serve their useful purpose only if the data acquisition system is reliable and fast. The manually operated point-to-point wireless communication system is becoming outdated day-by-day and hence there is a need to establish more modern communication systems such as telemetry through VHF/UHF/ Microwave or satellite. In such type of systems, no human element is involved for operation, collection and communication of data. This eliminates human error completely and reduces the time of observation and transmission of data. A typical system of forecasting for real-time operation consists of :

i) Observation and collection of operational data at sites,
ii) Transmission of data to forecasting centre,
iii) Formation of forecast.

Various hydrometeorological data acquisition systems and techniques of flood forecasting in river basins in India are:

(i) Manual observation/transmission and forecasting:

Rainfall data, river levels and flows are observed at fixed hours and are transmitted to the control room by P&T land line, telegram, telex or VHF/UHF voice transmission. Forecast is prepared with the help of correlation diagrams. This process requires significant time for forecast preparation. Delay in data transmission due to bad weather or faults in the communication system are quite common.

(ii) **Manual observation/transmission and computer system for forecasting:**

Data from field stations is transmitted by P&T land lines and also over wireless transmission. The delay to the extent of several hours is possible in data transmission and reception. The required data when fed to the computer program produces the forecast quickly.

(iii) **Automatic sensing, transmission and computer system for forecasting:**

Specified river gauge, rainfall, temperature and other hydrological parameters are measured with automatic recorders and are converted into electrical signals. These are transmitted with the help of repeater stations via VHF communication network. Master teleprocessor at the forecasting station coordinate transmission of data in specified sequence and interval. The data is then fed to computer system for producing the forecast.

(iv) **Link via Satellite:**

For the systems described above, the interruption in the communication of vital data is not completely ruled out. Moreover, the maintenance of the system is relatively costly.

A satellite based transmission system is more economical and reliable. It has the added advantage of overcoming the problem of congestion and widespread interference in all forms of radio communication.

By using satellite communication, the reliability of telemetry system is much more as data from each data collection station is directly transmitted to central station through satellite, i.e. one reporter station only. The specified river gauge, rainfall, temperature readings and other measured quantities are converted into electrical signals for transmission and are converted back at the forecasting station into a suitable form for framing the forecast.

For communication of telemetry data, land lines or radios are used. Direct communication via cables called land line telemetry generally employs either current, voltage, frequency position or impulses to convey information. Radio frequency telemetry employ either amplitude, frequency or phase modulation. In case of telemetry through radios, line of sight communication is used such as VHF, UHF and microwave etc. This system employs number of repeater stations to overcome earth curvature. Satellite communication eliminate all repeaters required in line of slight communication.

The various networks of telemetry system are :

Rivergauge network : On the upstream of forecasting point on the river, number of gauge sites are fixed for collection of data and period by period gauge observation is done.

Rain gauge network: At some locations in catchment self recording raingauges are fixed to record the rainfall. Each raingauge represents the rainfall of sub basin.

Communication network: Wireless stations are located at all the sites or nearby. For telemetry, VHF/UHF/Microwave or satellite communication is used.

The design of a sub-system for real-time data collection comprises of scientific design of data collection network, measurement of the data with desired precision and frequency. Scientific design of data collection network for operational flood forecasting is to evolve the total number of key stations for precipitation, river stage and discharge measurements, their efficient location based on certain scientific criteria for selection of each station, the time span and frequency of observation and determination of priority of network establishment.

Using inexpensive battery operated radios, as the communication link to the satellite, streamflow and other hydrological data can be collected in real-time via the satellite from the remotely located stations. The data collection platform consists of interface with the sensor and recording equipment and a radio transmitter and antenna. They operate at ultra high frequency. Data is collected, encoded in the required format and then transmitted with a unique identification code to the satellite. The rate at which the message is transmitted and it's length is determined by the satellite system. In addition, alert and interrogation facilities may be incorporated.

2.2 SPECIAL CONSIDERATIONS IN REAL-TIME OPERATION

The necessity for real-time operation arises from the fact that the inflows to reservoirs are random in nature and hence uncertain. To know the actual inflows in the reservoir and to forecast future inflows, adequate data collection and transmission network is required. The conditions prevailing in the area lying downstream of the reservoir play an important role in release decisions. In the event of a flood, operation of gates becomes an important aspect and needs to be given due consideration. In case, where it may not be possible to fully absorb the flood in the reservoir, efficient information dissemination system is required to warn the people downstream well in advance. Special considerations given to these aspects is briefly described here.

(a) Database Management For Real-Time Operation

Real-Time reservoir operation requires voluminous data/information handling and processing. Thus a good computerized database management system is very crucial for real-time operation.

The database management system consists of a collection of interrelated data and a set of programs to manipulate the data. The primary goal of any database management system is to provide an environment for storing information into, retrieving information from and manipulating information in a data base. A database management system consists of a large number of complex programs. It merely acts as a data librarian where data is stored along with the description of its format. It not only retrieves data correctly but also carries out integrated processing of data. It also eliminates data redundancy and inconsistency. Data accessing facility can be extended to multiple users by database sharing and data security constraints can be easily enforced.

All these advantages of using a database management system in data manipulation is possible if the amount of data to be handled is reasonably large and there exists relationship between different data items. Real-time reservoir operation is one such application domain where large amount of data has to be handled for generating required information.

The term 'Real-Time data' denotes the data that is transmitted to data collection, processing and dissemination centers as soon as it is collected in order to monitor or forecast water related phenomena for various practical operational purposes. The bulk of real-time data is required in connection with forecasting a flood event particularly in monsoon. Real-time data provides for early anticipation as rare events are taking place in the region, helps in efficint use of resources, enhances capabilities of project facilities and thus management of any extreme event.

For operating a reservoir in real-time, besides precipitation and discharge, information to account for the current state of the system, level of demands for various uses, conditions downstream of the reservoir and forecast of likely inflows is also required. The frequency of data observation depends on the purpose of the reservoir, varying from hourly to daily or weekly. Moreover, in real-time operation, data timeliness very crucial. Since real-time systems must obey strict computational deadlines, it is very essential that data be captured and transmitted rapidly before it gets outdated. During relative dry seasons, little variations will be observed in the data for several weeks. However, during atmospheric turbulences and during monsoons, data may have to be applied very rapidly. Hence the database management system for real-time operation should be so designed as to take least possible time in capturing, processing and transmitting the data to the forecasting centre where the optimum decisions may be taken.

Commercial database management systems can be used for developing database models for real-time operation. Many commercial systems provide Structured Query Language (SQL) for data definition as well as data manipulation of the data in database. Many packages also support interfaces to databases from programs written in languages like Fortran and C.

(b) Effect of conditions on the downstream of a reservoir

The hydrometeorological conditions in the basin downstream of a reservoir play an important role while making real-time release decisions. During the flood season, a part of the flow in the river downstream of reservoir is contributed by the free catchment area. In case of heavy downpour, flow from this free catchment at any location can be considerable and release from the reservoir should be such that the total flow at the damage centers does not exceed the permissible limits.

Another way the release decisions at the reservoir are affected is because of the change in irrigation demands. If rainfall has occurred in the command area of the reservoir and the soil has attained sufficient moisture for the growth of crops, irrigation demands for that time will get reduced which can affect the release decision at the reservoir.

Thus to summarise, in real-time operation, forecasting of flow in the river from the area lying downstream of the reservoir should be considered and the model giving the release decisions should take into account the conditions of the downstream area also.

(c) Gate operation

Gate operation is an important aspect of real-time operation. The gates can be operated manually or mechanically. In the manual system, there is non-uniformity in operation and the rate of operation is also slow. The advantage of the mechanical system is that the gates can be rapidly operated, uniform rate of opening and closing can be maintained and there are less chances of human error. Moreover, at the time of floods, the meteorological conditions such as wind, rain thunder etc. are not appropriate for the human element to operate the gates. In these circumstances, mechanical system is most suitable.

In real-time operation, if some emergent situation arises, gates are to be operated in accordance with the requirements as early as possible and the time taken for such operation becomes an important parameter as far as safety of dam and flooding of downstream area is concerned.

(d) Information dissemination

Whenever heavy outflow is likely to let off from the dam or whenever breaking of dam is anticipated, it is the duty of officer in charge of reservoir operation to intimate the exact details situation to higher authorities and to communicate the warnings to Police, Revenue and Panchayat authorities and general public for taking necessary precautionary measures in respect of alerting and evacuating the people in the area likely to be affected, if required.

Full advantage of real-time operation is possible only when a good information dissemination system exists in the basin. Real-time operation forecasts well in advance about the likely outflow and if the public is informed in time, then a great deal of flood damage can be reduced effectively.

2.3 ADVANTAGES OF REAL-TIME OVER CONVENTIONAL METHODS

For real-time operation, data collection and transmission is needed at short time interval which requires setting up of telemetry network. This involves high cost but the advantages which result from real-time operation overrun the expenditure incurred for creating facilities for such operation. The advantages of real-time operation over conventional methods are as follows:

(a) Real-time operation has high flexibility in comparison to the conventional methods. It takes into account the current state of the system and forecast future inflows which are not considered in conventional methods. It is the most realistic operation for reservoirs as it continuously updates the operation with the flow of information.

(b) In case of emergency such as floods, it gives high lead time to the public to take precautionary measures in respect of alerting and evacuating the area likely to be affected.

(c) It provides for efficient utilization of water resources.

REAL-TIME OPERATION STUDIES

3.0 REVIEW OF STUDIES

Water resources system models can be classified as deterministic if the streamflows are assumed known and probabilistic or stochastic if only the probability distribution of the streamflows is known. Although the stochastic models are more complex and require more computation time, the information supplied by them is more useful and due to this reason, they are in vogue nowadays.

Optimization models optimize the decision maker's choice which is expressed by an objective function. The choice is further subjected to a set of constraints which arise due to physical limitations, law of nature, and resources availability etc. The solution is given in terms of specific values of decision variables which will give the best value of the objective function.

The choice of objective function is a very important decision for an optimization formulation. In the operation of a reservoir, a large number of alternatives are available to the decision maker. The benefits from each alternative decision can be measured in terms of a common monitory unit or crop yield or quantum of energy generated etc. Now to choose a particular alternative, it is necessary to order them in terms of attainment of the objective of the planner. The criteria used in this ordering or ranking is called the objective function.

The nature of the problem is another factor upon which the design of objective function depends very much. If the problem is of short term operation, the aim may be to evolve a policy which meets the targets as closely as possible. For example, for problems of flood control operation, objective may be to minimize the flood damage, or it may be to minimize the flows which are greater than the safe carrying capacity of the channel. However, for conservation operation, the aim may be to minimize the deviations from the long term targets. Another interesting problem is the multipurpose operation of a reservoir. In this case the objective function should be designed such that all the purposes are given appropriate weight.

Out of various optimization techniques discussed, two have been most commonly used for reservoir operation problems. These are linear programming and dynamic programming. Mostly dynamic programming has been used in cases where objective function is non linear. The user of integer programming is mostly for capacity expansion problems. Stochastic programming in conjunction with LP or DP has also been widely used. Becker and Yeh (1974) developed an algorithm for optimization of real-time operation of a multiple reservoir system. It was assumed that various uses and purposes are quantifiable via a set of constraints which take care of them, for example, storage allocation for flood control purposes, for hydroelectric generation and for recreation uses etc. They defined the best state in each period as the set of reservoir storage which possesses the largest total stored potential energy related to the installed power houses. An attractive feature of the work was that they used a LP-DP formulation was used in this study. The LP formulation was used to determine the optimal reservoir releases and storage states for each period of total time interval of interest. It had an objective function which minimized the stored potential energy losses. The stored energy in the reservoirs was expressed in terms of the states of reservoirs and the corresponding energy rate functions. The LP algorithm was used to generate solutions for different values of the on-peak energy generation constraint and corresponding alternative paths from starting vector to ending vector space. Next a DP formulation was used to select from these alternatives an optimal path from any period i to each of the incremental energy levels of period (i+1). This was done by choosing the alternative which maximizes the sum of components of the end-of-period storage vector. The cumulative energy was chosen as the state variable for the DP algorithm while the feasible energy constraint for a period formed the decision variable. The final result was a policy which maximized total on-peak energy generation over and above contract levels and produced a satisfactory starting state for the next set of periods to be considered. The algorithm was illustrated through application to the Central Valley Project of California.

Chu and Yeh (1978) studied the optimization of real-time operations for a single reservoir system. The objective was to maximize the sum of hourly power generation over a period of one day subject to constraints of hourly power schedules, daily flow requirement for water supply and other purpose, and the limitations of the facilities. The problem had a non-linear concave objective function with non linear concave and linear constraints. Non-linear duality theorems and Lagrangian procedures were applied to solve the problem where the minimization of the Lagrangian was carried out by a modified gradient projection technique along with an optimal determination routine.

The concept of real-time optimization of reservoir operation has been applied to California Central Valley Project by Yeh et al (1979). The system consists of 9 reservoirs, 9 power plants, 3 canals and 4 pumping plants. The overall procedure is to optimize in turn a monthly model over a period of one year, a daily model over a period of one month and an hourly model for 24 hours. Outputs from one model are used as inputs into the next echelon model, iterating and updating whenever new information on streamflow prediction becomes available. The hourly model is the one that is used for scheduling hourly reservoir releases. It maximizes a weighted summation of generated power over a 24-hour period subject to specified plant releases obtained from a daily model, a desired hourly power schedule and appropriate system and equipment constraints. The optimization procedure involves an integrated LP. The CVP operational records of some typical days are compared with the hourly model outputs for those days and significant improvements are observed both in better conformance with the desired power schedule and more efficient hydropower production.

Houck (1982a) investigated the use of mathematical programming models for real-time reservoir operation. Two measures of the quality of the operations designated by the mathematical programming models are (1) the total value of actual penalties (surrogate for costs and benefits) incurred by the operation and (2) the closeness of the physical operations designated by the model to the physical operations of the theoretically best operations. Out of the five different types of objective functions used in the models, two were clearly superior to the others. One of these requires trial and error fitting of a multiparameter objective function; the other does not. The model which does not require trial and error parameter fitting may be used to operate a reservoir system either when correct benefit and loss functions defining the effects of operation are available or when only descriptions (in the form of cumulative distribution functions) of desirable physical operations are available.

The daily operation of a reservoir system requires the balancing of long term operating goals, short term restrictions on operation due to the physical capabilities of the system, and imprecise information on future streamflows. Houck (1982b) investigated the use of an optimization model for the real-time reservoir operation. It is shown for a test case that the objective function of an optimization model used for real-time operation should differ from the true objective or measure of effectiveness of reservoir operation. Simulation of real-time operation is employed to demonstrate the significant improvements that can be achieved with different real-time objective functions. In it's simplest form, the objective of the operations can be defined as minimize the sum of penalties or losses associated with deviation from ideal operation. Target storage volumes, target release rates and target downstream flow rates represent the ideal operations. Deviations from these targets above or below, represent non ideal operations and are assessed penalties. The actual shapes of the penalty functions are determined by the relative importance and magnitude of each type of deviation from ideal operations. The problem is further complicated by a lack of good forecasts of future inflows. The hypothesis tested in the study is: Because of the limited forecasting that is included in operating models, better actual operations may be obtained by using penalty functions not equal to true penalty functions. This does not mean that true penalty functions are ignored. Actual operation of the reservoir can be evaluated by measuring the true penalty incurred.

It is possible to define the real-time reservoir operation problem as a mathematical program. This program typically includes a non linear objective to minimize the penalties associated with operations that deviate from ideal operation. Because the operation time step is sufficiently short, the river flow dynamics are also typically included.

The modeling of the river flow dynamics and the non -linear objective function combine to produce an inseparable mathematical program. Therefore, according to Toebes et al (1982), dynamic programming is not suitable as the solution technique.

Real-time operation is the period -by -period operation of the reservoir. Risk assessment is made as a means of quantifying the effects of managerial intervention in the implementation of physical operation. Simulation of real-time operation on the computer provides a procedure to obtain a large sample size of operational results from which risk of failure may be calculated. Hinton et al (1982) presented a methodology for the assessment of risk of failure that is in accordance with real-time operational practice. To achieve a specific benefit, the operational management inherently accepts a level of risk of failure. Risk is defined as the total probability of exceedence of a design criterion. The design criterion is a pre-specified degree of failure. A failure is said to occur when there is a gap between what is demanded of the system and what the system can supply. To follow a specific operational strategy, the decision maker weighs the potential benefits to be received against potential disbenefits which result because of risk of failure. The incorporation of risk of failure in real-time operation requires that risk so calculated be made directly compatible with the period-by-period operational practice.

Buchanan & Bras (1982) and Bras et al (1983) developed a stochastic dynamic programming algorithm for real-time adaptive closed loop control of reservoirs. In the control theory, two types of approaches have been suggested open loop and close loop. In the open loop control, release R(n) are specified for all time period, n =1, 2...N, at the beginning of an N-period planning horizon. In close loop approach, each release R(n), n=1,2......N from the reservoir is given as a function of the state of the system to be observed at time period n. The solution period consists of finding the optimum solution using the stochastic dynamic programming for the next K periods where K is the horizon for which the forecast inflows are significant. The inflow values and their transition probabilities are updated using the available forecasts before the optimization is performed. This approach was applied to High Aswan Dam (HAD) as a case study. The HAD is a multipurpose project with three main objectives as irrigation, hydroelectric power, and flood control. The objective function was taken as the sum of weighted squared deviations of actual releases from the target releases for each of these purposes. The squaring of deviations indicated increasing loss with each extra unit of deviation from the targets. The weights adopted indicate a heavy preference for meeting the irrigation demands, a secondary preference for avoiding downstream losses due to higher releases and least preference for energy generation. The authors considered flood control with other purposes without giving it any special weight. It was however mentioned that a more representative objective function could be chosen which may give improved performance of the system. The optimum solution was obtained using a stochastic dynamic programming algorithm. It was concluded through a simulation study that the discounted adaptive policy is better than the discounted steady state policy. An important feature noted by the authors was that each month's release policy essentially reproduces the zonal concept of reservoir operation.

Yazicigil et al (1983) developed and applied a model named GRBOOM for real-time daily operation of multipurpose reservoir system. The GRBOOM is a linear programming formulation whose objective is minimization of sum of all daily penalties over the operating horizon (usually 1-5 days). The constraints of the problem include reservoir mass balance constraints, storage zone constraints, control station mass balance constraints and flow zone constraints. The range of flow variables was limited by specifying certain inequalities. The maximum allowable release from a reservoir was made dependent upon the magnitude of some uncontrolled tributary flow. The constraints were also included to limit the rate of change of reservoir release to some acceptable value. The channel routing was performed using a multi-input linear model. The penalties for deviations in different zones in reservoir and for channel flows were specified using the concept given by Sigvaldason (1976). The objective function representing the sum of all penalties during the operation horizon associated with undesirable conditions was to be minimized. The model was built to accept forecasts over some specified time horizon. Using these, a set of releases were determined which are optimal for the chosen horizon. However, releases for only one day ahead period were implemented. The releases for remaining days were to be revised during the next model run as updated forecasts are made available. The length of this time horizon is decided keeping in view the marginal improvement in system performance and cost of additional computational burden. A comparison of the results of model run with the historical operation showed that there was a substantial reduction in flood peaks at control stations by adopting optimal releases as suggested by the model. The model- derived reservoir elevations had less deviation from the rule curve as compared with historical elevations.

Bauwens et al (1983) described a model for real-time management of a single purpose flood control reservoir being operated to ensure that the reservoir releases and local inflows from the uncontrolled intervening basin do not cause flooding at a downstream control point. A conceptual rainfall runoff model was used to forecast the discharge from the uncontrolled intervening catchment area. This information was used to decide the releases from the reservoir.

Wasimi and Kitadinis (1983) modeled the dynamics of a multireservoir system by a set of linear differential equations (state space formulation) and employed a quadratic penalty objective function track. Relating reservoir inflows to Gaussian rainfall inputs via a reduced order state space unit hydrograph model, they formulated a linear, quadratic Gaussian control problem and solved it analytically. The scheme was found to be suitable for operation under moderate flood conditions when capability constraints were not likely to become binding.

Can & Houck (1984) applied primitive goal programming to the real-time, daily operation of multipurpose, multi reservoir system. A significant advantage of goal programming approach is that it may be based on physical operating criteria. It does not require the penalty benefit functions that may be difficult to define but are essential to other real-time operating models. Therefore it is easier to implement. Goal programming model is applied to the Green River Basin (GRB) system comprising four multipurpose reservoirs. The operations resulting from goal programming are compared to operations resulting from another optimization model which is more data intensive and which was designed specifically for the GRB system. Both sets of operations are comparable in their effectiveness, although in some cases goal programming operations are better. A hierarchy of goals, expressed in terms of storages and releases define the operations objective of the goal program. Attainment of the goals is sought sequentially beginning with the highest priority goal. Only when a goal is attained, consideration is given to the next lower priority goal. The procedure terminates when a goal that cannot be fully attained is encountered.

Orlovki et al (1984) presented a deterministic (min-max) approach to real-time operation of a multipurpose reservoir. Two management goals namely satisfaction of water demand of the downstream uses and attenuation of the storage peaks in reservoir have been assumed. Since the goals are conflicting, the solution of the problem will be a set of efficient operating rules. Many different methods for such operating rules have been developed but they deal with uncertainties in description of objectives and constraints. One common feature is the use of notion of probability to describe future inflows and evaluate system performance. Very frequently, reservoir managers react in an unfavourable way to optimization methods. Reasons for this may be inadequate description of the physical characteristics of the system, the complexity of proposed algorithms and the feeling that single value operating rules are tools too rigid for solving complex but soft decision making processes. In most cases, decision makers are risk aversers even if it entails a worse average performance of the system. Deterministic (min-max) approach overcomes many of the above criticisms. In this approach, the performance of the system is evaluated with reference to a few specific inflow sequences suggested by the manager. These inflow sequences may be real or synthetic inflow records or some hypothetical sequences of inflow which the manager considers as well suited for testing the reliability of any operating rule. Of course, the solutions suggested by this approach will be dependent on the input data. For this reason, one must be particularly careful when selecting these sequences. The use of this method is particularly justified when the effort of the manager is mainly focused on avoiding substantial failures of the system during severe hydrological episodes. This approach does not require complex algorithms and on-line optimization. Moreover, when the reservoir is not too full or too empty, the method suggests a whole range of possible releases instead of a single value, thus introducing some flexibility into the decision making process. The key data necessary for application of the method is a 1 year long daily inflow sequences. The operating rule can be interpreted in terms of storage allocation zones the boundaries of which depend upon the forecast of daily inflow. The analysis of a real case has shown that this deterministic approach is quite powerful in pointing out the possibility of improving the performance of a reservoir in operation.

Datta and Houck (1984) developed a real-time operation model useful for daily operation of reservoirs. The model is based on a chance constrained formulation and assumes a particular form of the linear decision rule. It was the conditional distribution functions of actual streamflows conditioned on the forecasted values. These CDFs are constructed by incorporating the statistical properties of forecast errors for different time steps. The objective considered is then minimization of weighted probable deviations from storage and release targets. With the use of target values for release and storage, this model is capable of using a release policy that is a sub set of a seasonal policy and overcomes the short sighted nature of operation. Simulation of actual operation demonstrates the feasibility and efficiency of this approach. The restrictions associated with the use of a linear decision rule are shown to be invalid for this model.

Can & Houck (1985) demonstrated two problems associated with the implementation of optimization models to real-time reservoir operation. The first problem is due to the use of imperfect forecast information for the reservoir inflows. The performance of the model depends on the operating or forecast horizon. It is clear that if the forecast information is highly reliable or perfect, then models yield better operation as the operation horizon increases. But, on the other hand, as the forecast horizons increases, the reliability of forecast decreases, and extending the operating horizon may not improve the operation. As illustrated with an example, a trade-off has to be made between the reliability of forecast information and the operating horizon to be used in the real-time operations model. The second problem investigated in the study is due to the use of approximate routing models relating reservoir releases and d/s control points. If the optimal reservoir releases obtained by using an approximate routing model are implemented, the actual flows at the d/s control points could be far from being optimal. A comparison of the results of model run with the historical operation showed that there was a substantial reduction in flood peaks at control stations by adopting optimal releases as suggested by model. The model derived reservoir elevations had less deviation from the rule curve as compared with historical elevations.

Wang and Adams (1986) presented a real-time reservoir operation model. In this model the inflows were described by a periodic Markov Chain. A two stage optimization technique was applied consisting of a real-time model followed by a steady state model. The operation horizon was divided into three phases. The operation of the reservoir in the periods which fall in phase I is influenced by the current conditions of the system and was termed real-time operation in this study. The inflows to these phase I periods are represented by a sequence of instantaneous inflow state distributions, which are obtained from the transition of the inflow Markov Chain for the given actual inflow in the previous period to current period. In the real-time model, the optimal release decision for the current period only is determined based on current storage state and preceding periods inflow using the value iteration routine. The periods in phase II are far enough from current period and are not influenced by current conditions. They are defined to be steady state operation periods. Examining from the current period, the inflow probability distribution for the periods in phase II will converge to their respective monthly limiting distributions. The periods in phase III are not of practical interest since they are too far in future. It was claimed by the author that this strategy leads to significant reduction in computer time. Through a case study involving a multipurpose reservoir, it was shown that the derived optimal operating strategy results in improvement over the conventional strategy to the time of 14% for the average annual reward and 3.6% for the annual energy production.

Georgakakos and Marks (1987) introduced a new method for real-time operation of reservoir systems. The system is represented by a set of stochastic differential equations describing the reservoir and river dynamics in state space form. The formulated reservoir operation problem calls for finding policies which maximize the expected benefits of one systems' objective while satisfying the remaining objectives at prespecified reliability levels. The solution is obtained by a new method named extended linear quadratic Gaussian (ELQG) controller. It is so named because it is applicable to LQG problems as well as problems with non linear dynamics, control and reliability constraints and non quadratic performance indices. The new method accounts for system uncertainties and is designed to display computational efficiency and reliability. The method was tested for the control of High Aswan Dam. ELQG displayed reliability and computational efficiency even for very long control horizons.

Jain (1990) developed a flexible arrangement for operation of reservoir based on the state of the system. The approach is based on the stochastic dynamic programming technique. The formulation aims to maximize the reservoir storage at the end of the flood season subject to the constraint that the risk of an overflow of the reservoir between the current time and the end of the flood season is kept within permissible limit for each time period. To test the efficiency of the approach, the policy has been applied to the Dharoi reservoir in Sabarmati basin. The daily inflow data of monsoon period for 31 years has been used to develop the operation policy. A detailed simulation study was undertaken to test the performance of policy. The performance of the policy was found to be excellent as it was possible to optimally satisfy the two conflicting objectives of flood control and conservation purposes.

Mohan et. al. (1991) developed a methodology for real-time reservoir operation both for monthly and weekly periods of operation of a reservoir system. The methodology consists of three phases. Phase one is the determination of operating policies using dynamic programming regression approach. Phase two is the development of forecasting model and phase three is the real-time simulation model which uses the forecast of inflow from phase two to derive the optimum policy from phase I. The methodology has been applied to the Krishnagiri reservoir system in Tamil Nadu. Two policies for operation were also tested using this methodology. The real-time simulation results, when compared with historic operation resulted in significant reduction in irrigation shortages for both the policies.

The operation based on the methodology of real-time reservoir operation has performed better when compared to the historical operation.

CONCLUSION

Due to increase in population and urbanization, the conservation demands as well as damage potential of floods are increasing day by day but it is not so easy to create new reservoirs because of social and environmental ramifactions. So it is the need of the hour to operate the existing reservoirs as efficiently as possible. Real-time operation is an efficient way of operating a reservoir system in which the control decisions are taken on the basis of prevailing conditions of the system and forecast about the likely inflow in the reservoir. For real-time operation of a reservoir, automatic telemetry system is essential for direct transmission of data at regular interval to the forecasting station from where the forecasts about the likely inflow are issued. This reservoir inflow forecast is used as an input in the operation model to find the optimized value of release from the reservoir.

A lot of work on real-time operation is going on and efforts are on to develop optimization models which require lesser computational time. Computation time is an important aspect in real-time operation as the 'lead time' of a forecast is affected by it. A number of models using different optimization techniques like linear programming, dynamic programming and goal programming have been developed and applied to various real life problems in the form of case studies.

For real-time operation, in comparison to simulation, optimization techniques have mostly been used and preferred because optimization techniques quickly decide about the release once the demands, present and future inflows and downstream conditions are fed to optimization models. Simulation, on the other hand, is a trial procedure and does not decide about the release directly and quickly.

It can be concluded that by the increasing prevalence of high capability but low cost process control computers with connected telemetry networks and remote control features, the technical support for the real-time operation of reservoirs is today realisable.

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