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MULTIPURPOSE OPERATION OF A RESERVOIR

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1985-86

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ABSTRACT

Reservoir operation forms a very important part of planning and management of water resources systems. 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.

In case of a single purpose reservoir, the aim is to find the optimum amount of water to be released from the reservoir given the amount of water available in the reservoir, future demands and any information available about the inflows which are likely to enter the reservoir. For a multipurpose reservoir, in addition to the above, it is also required to optimally allocate the release among several purposes.

The basic guideline which is available to a reservoir manager is usually in the form of rule curves which specify the reservoir levels to be maintained during different times of a year. As it may not always be possible to adhere to rule curves, guidelines are also given as to how the deviations should be adjusted.

In this report, various procedures used to develop rule curves for a single purpose and multipurpose reservoir have been described. It is also discussed as to how to arrive an optimal decision in case of an unforeseen event. New techniques of determining reservoir operation procedure like simulation, optimization and real time operation have also been discussed.

1.0 RESERVOIR OPERATION PROCEDURES

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

Among the various components of a water resources development project, reservoirs are the most important. These are created by constr—rucing dams across a stream. A reservoir is the best way to regulate stream flows. Depending upon the natural inflows and demands, water is either stored in the reservoir or supplied from the storage. Simultaneous to the process of storing water, a reservoir can conserve the fall in the stretch of river for generation of electrical power. In case of flood control projects, it can provide empty space for storage of flood water thereby mitigating the peaks. A reservoir also provides pool for navigation to negotiate rapids, habitant for aqualife and facilities for recreation and sports. It enhances scenic beauty, promotes afforestation and wild life.

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 for apportioning of storage among purposes and effect releases in different time periods in accordance with the demands. Sometimes it is also required to specify whether water is to be withdrawn from upper layers, lower layers or both to provide water of suitable temperature and quality when such releases are necessary from biological considerations.

At the time of design of a reservoir project, an operating policy is formulated using which, the benefits can be harvested in best possible manner. Two factors which play important role in this decision making process are knowledge of likely future water availability to the operators and the length of decision time period. Usually the length of this time period is one month in the studies during the planning stage except for the studies dealing with flood control. At the time of actual operation, the time period is divided into smaller units and the benefits are suitably distributed. The foreknowledge of future inflows is dependent upon the forecast capabilities. With past hydrological data, catchment characteristics and a study of trend, a reasonably good forecast of future streamflows can be made after studying the runoff generation process.

In past the determination of operating policies was, to a very large extent, based upon personal judgement. As pointed out by Buras (1972), the rules were generally simple and sufficient alternatives were not analysed. As the water resources systems became more complex, the problem of operation drew attention of researchers which led to development of better and refined procedures. This has also been necessitated because of higher pressure of economically efficient utilization of limited water resources. A detailed reservoir operation procedure should be able to guide the operator to take decisions under most of future situations which are likely to arise.

1.1 Functional Requirements of Various Uses of Water

The complexity of the formulation of 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.

1.1.1 Irrigation Requirements

The irrigation requirements are seasonal in nature and the variation largely depends upon the cropping patterns in the command area. The irrigation demands are consumptive in nature and only a fraction of the water supplied is available to the system as return flow. Further, these requirements have direct correlation with the rainfall in the command area; high rainfall leads to low demands and vice versa. In general, the demands will be minimum during the monsoons, and maximum during winter and summer months. The average annual demands remain more or less steady unless there is increase in the command area or large variation in cropping pattern from year-to-year. 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.

1.1.2 Hydroelectric Power Needs

A reservoir operated to produce hydroelectric power seldom operates in isolation. The energy developed is normally fed to a regional grid from which the users draw their share. This grouping of a number of hydro and thermal and/or nuclear power plants provides, on one hand,. efficiency, economy and flexibility in their operation and makes possible increased power and energy generation on the other hand. This grouping, however, makes their operation quite complex.

The hydroelectric 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. The hydroelectric power generation comes under non-consumptive use of water because after passage through turbines, water can again be utilized for consumptive uses downstream. The amount of hydroelectric power generated at a plant depends upon the volume of water passed through turbines and the effective head. Most hydroelectric plants are part of an interconnected system and therefore there is considerable flexibility in coordinating power needs of water with other needs of water. In the extreme, the power production at a hydroelectric plant may be limited to those times when the releases are necessary either for other uses or to discharge excessive water.

1.1.3 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 demands also increase with time due to higher aspirations of the people because of rise in their standards of living within a particular year; the seasonal demand peak is observed in summer. For the purpose of design a target value is assumed by making projections for population and industrial growth. The supply system for such purposes is designed for very high level of reliability.

1.1.4 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 attentuation depends upon the empty storage space available in the reservoir when the flood meets it. This in turn decides the volume of inflows which can be temporarily stored in the reservoir. Clearly, achievement of this purpose requires the availability of empty storage space in the reservoir. As far as possible, the releases from the storage are kept less than the safe capacity of downstream channel. After passage of one flood peak the empty storage space is again available for flood control.

1.1.5 Navigation

Many times storage reservoirs are designed to make a stretch of river constituting the reservoir navigable or to make release of water downstream to maintain sufficient flow depth in the stretch of river channels used for navigation. The water requirements for navigation show a marked seasonal variation. Obviously, there is seldom any demand during the monsoon period when sufficient depth of flow may be available in the channel. The demands are maximum in the dry season when large releases are required to maintain required depth. The demand during any period may also depend upon the type and volume of traffic in the navigable waterways.

1.1.6 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 recreational benefits are incidental to other uses of the reservoir and rarely if at all, a reservoir is designed or operated for recreational purposes except in highly developed countries. The recreation activities are best supported by a reservoir which remains nearly full during the recreation season to permit boating, fishing, swimming and other water sports. Large and rapid fluctuations in water level of a reservoir are harmful from the recreational points of view as they can create marshy lands near the rim of reservoir which are unsightly and create problem in maintaining docks, boat moorings, beaches and other waterfront facilities in usable condition. They also necessitate frequent shifting of picnic paraphernalia.

1.1.7 Water Quality Control

The maintenance of adequate flows in the channels downstream is also one purpose for which reservoirs are developed. Usually, this may fit in the pattern of releases for other purposes. In some cases, the reservoir may be operated to control mosqueto growth by rapid fluctuations of water level which strand larva on the shore. In some cases, the reservoirs are also operated to control thermal quality by releasing water of desired temperature from the consideration of aquatic life.

1.1.8 Fish and wild life preservation

The construction of a reservoir leads to changes in the river regime and ecosystem. It may result in major changes in habits of existing wild life. It is necessary to ensure that these changes are not harmful to those species. The fishes depend upon water for their existence and also require free movement in the upstream and downstream directions. Protection of existing fisheries requires provision of fish ladders at the obstructions such as dams and barrages for their movement. Further, wide and rapid fluctuations in reservoir water level are harmful to fishes, particularly during spawning period when they may be caught in marshes. Complete stoppage of flow below dams is also destructive to fishes and wild life.

1.2 Classification of Reservoir Operation Problems

Depending upon the number of purposes which a reservoir is to serve, the reservoir operation problem may be classified as single purpose operation problem or multipurpose operation problem.

1.2.1 Single Purpose Reservoir Operation

A single purpose reservoir is constructed to serve only one purpose. Therefore the operation problem is to decide about the releases to be made from the reservoir so that the benefits for that purpose are maximized. Typically, the purposes which the reservoir is required to serve may be either conservation purposes such as water supply for irrigation, navigation, municipal and industrial needs, and generation of hydroelectric power or flood control. In case of a reservoir serving the conservation purpose the magnitude of benefits which could be derived from the reservoir depends upon the yield of the reservoir and therefore, more is the water available from the operation of reservoir, larger would be the expected benefits. For hydropower reservoirs, the benefits depend not only on the yield of the reservoir but also on the head available for power generation.

The benefit function is not linear in all the cases. This amounts saying that the benefits obtained by supplying two units of water to a particular area will not always be just half of the benefits accrued by supplying four units of water. Moreover, the benefits may vary from time to time, i.e., the benefits derived by supplying one unit of water to crops in the month x may not be the same as benefits derived by supplying same amount of water in the month y. Besides this, in case of hydroelectric power, there is one more complication because the amount of power generated is a function of not only the quantity of water released but also the operative head.

The benefits from operation of a flood control reservoir depend upon the extent of moderation of floods by the reservoir and the damages saved. The benefit function is not linear in this case too. The degree of moderation of floods depends upon the volume and peak of flood hydrograph and the empty space available in the reservoir at the time when flood impinges it. The damage saved will depend upon the area saved from inundation and the land use.

1.2.2 Multipurpose Reservoir Operation

A multipurpose reservoir is developed to satisfy more than one purpose. Typically, the purposes may be a combination of flood control, irrigation, municipal and industrial water supply, hydroelectric power generation, and navigation. The purposes which are best served from the water stored in the reservoir are termed conservation purposes. These purposes include irrigation, municipal and industrial water supply, navigation and hydroelectric power generation. The flood control requirement is different then the conservation aspect and is best served if the reservoir is as much empty as possible. Multipurpose reservoir operation involves many complex problems as none of the possible uses are entirely compatible with each other. The basic factor in multipurpose operation is compromise and efforts are required to be made to make the different purposes in as much agreement as possible.

1.3 Compatibility of Multipurpose Uses

Several water uses such as irrigation, navigation and water supply require a volume of water which cannot be jointly used and thus these uses are not compatible with each other. A reservoir created for these consumptive uses must provide a clear allocation of storage space to each use. However, since hydrolectric power generation is a non-consumptive use, water released for other purposes can be used for power generation. If the power plant is operated as a base plant, its water requirements may fit, to a great extent, with the releases for other uses. However, in case of power plants for peaking, an after bay or re-regulating/balancing reservoir downstream will be necessary to smooth out fluctuations of power releases. In case the seasonal variations in power demand do not coincide with requirements of other purposes, a certain amount of storage may have to be allocated for power use, unless there are other plants in the system to pick up load during such periods.

The recreation benefits from a reservoir are taken as opportunity permits. In some cases, it may be possible to plan reservoir operation in a manner that it is not drawn down excessively during the peak recreation season. Where heavy drawdowns are unavoidable, an area of the reservoir may be closed off by a small dam to create favourable conditions for swimming and other water sports. Similar arrangements may be necessary for fish and wild life preservation also. The subimpoundment for recreation and wild life is a permanent allocation of storage for these purposes. If a minimum flow is to be maintained for water quality maintenance, it may require a separate allocation of storage, unless, flows for other purposes are adequate from this consideration too.

The requirement for flood control is empty storage space as opposed to conservation purpose and this is least compatible with conservation purposes.

1.4 Conflicts in multipurpose reservoir operation

The conflicts which arise in multipurpose reservoir operation may be classified in three main headings:

a) Conflicts in space,

b) Conflicts in time, and

c) Conflicts in discharge.

Each of these is being discussed now in details:

1.4.1 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 the storage space can be clearly allocated for each purpose. As an example, it may happen in a particular case that a reservoir is to be constructed which would serve for conservation purposes as well as flood control. Certain volume of upper storage of the reservoir can be reserved for flood control and the remaining storage can be reserved for conservation purposes. 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 monsoons to meet the conservation demands. Thus, in reality, this multipurpose reservoir is a combination of single purpose reservoirs.

Another situation can be imagined in which a reservoir is being used for recreational activities or fish and wild life preservation alongwith other uses. Fluctuations in reservoir level which are either too rapid or too big in magnitude may be harmful for these purposes. Moreover, rapid drawdown is also injurious for the life of young fishes who may not be able to keep up with the receding water and die on the mud flats. Separate allocation of storage for this may be made on an arm of the reservoir.

1.4.2 Conflicts in time

The temporal conflicts in reservoir operation occur when the seasonal use pattern of water varies with the purpose. The conflicts arise because releases for one purpose may not agree with the other purpose. For example, the irrigation demands show a considerable variation depending upon the cropping pattern, season and rainfall while the hydroelectric power demands may have a different seasonal variation. If a reservoir is serving for these two purposes then at a particular time, water may have to be released for power generation although there may not be any irrigation demand and thus from the point of view of irrigation, it is wastage unless there is some other way to conserve it downstream. Similarly, if water is released from the storage considering irrigation as the governing factor, the power generation may be affected when there is less demand for irrigation. There is no problem if water availability is in abundence . However, this seldom is the case and therefore, in such situations, the aim of deriving an operating policy is to optimally resolve these conflicts.

1.4.3 Conflicts in discharge

The conflicts in daily discharge are experienced for a reservoir which serves 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. At a power house which is acting as a peaking plant, releases are maximum at the daily peak demand time and are minimum during the period of low demand while more or less uniform supply is required for purposes like irrigation, water supply and navigation. Many times a small conservation pool is created on the river downstream of the power house which is used to damp the oscillations in power house releases. If the intake for water for irrigation, water supply or navigation is located at a sufficient distance downstream of the reservoir then these oscillations damp out themselves considerably.

1.5 Types of Reservoirs

Depending upon the storage provided, a reservoir may be classified in two groups

a) Seasonal storage reservoir,

b) Over year storage reservoir,

1.5.1 Seasonal Storage Reservoirs

These reservoirs are designed to serve conservation purposes for a limited period of low flows, say one or two months. These reservoirs fill up and spill quite frequently. These reservoirs are normally constructed on small tributaries and serve relatively smaller area. The reservoir may also give certain incidental flood control benefits.

1.5.2 Over year storage reservoirs

In these type of storage reservoirs, water available in the storage at the end of one year is carried over to the next year. These reservoirs may neither fill nor become dry every year. While designing these reservoirs, seasonal fluctuations of inflows and outflows are not considered.

1.6 Scope of the present report

The objective of the present report is to describe the various methods used to derive the reservoir operating rules. The procedures used to derive rule curves have been described in detail. With the advent of computers and developments in operation research theory, the application of system engineering techniques in reservoir operation is growing day-by-day. The techniques of simulation and optimization for reservoir operation are also described in this report.

2.0 RESERVOIR OPERATION PLANNING

2.1 Operation of Conservation Reservoirs

The reservoirs serving the conservation uses fall generally in two categories as discussed below:

2.1.1 Reservoirs designed for multiannual storage

In case of this type of reservoirs, the operating policy is based on long term operation of reservoirs. 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. The study is normally carried out for time period of 30 years or longer (using historic and/or synthetic generated flows) so that the data used covers the periods of low, medium and high flows and the regulation policy can be derived for different conditions of operation. The flood control benefits, to a large extent, are derived automatically because the majority of floods are absorbed in the reservoir.

If hydroelectric power generation is not one of the purposes of the reservoir, the water is allocated among various consumptive uses. The share of priority rights downstream and for releases from the point of view of water quality maintenance is taken into consideration to arrive at minimum acceptable flow to be released downstream. 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. The problem can, however, arise in periods of drought not anticipated earlier. During these times, based on prespecified priorities, the supplies for some uses is curtailed keeping in view bare minimum demands of each purpose. Ofcourse, consideration is given to the maintenance of essential services even if it is at the cost of agricultural or industrial production. Many times, it may be necessary to risk a future crop to save damage to the standing crop. If generation of power is one of the purposes of the reservoir the problem becomes little complex. The releases for consumptive uses are routed through the power house to generate the required energy. Here two distinct cases may arise. In case the water demands for hydroelectric power generation are more than the consumptive use demands taken together, the additional releases for power generation may be made if so planned. The extent of water releases for various uses including hydropower generation which can be served by the reservoir storage on long term basis are then determind taking into account the obligatory releases required from the consideration of water rights etc. However, in case the water demand for consumptive uses is in excess of the requirement to satisfy hydroelectric power demands, the additional releases for power generation may be restricted to the periods when demand for consumptive uses is negligible. If necessary the supplies for some of the uses may also have to be curtailed based upon the prespecified priorities.

2.1.2 Reservoirs designed for seasonal storage

The operating policy of reservoirs designed and operated for seasonal storage is based on yearly operation. The reservoir operation study is carried out for long term record of 30 years or more using historical as well as generated flow data taking into account the demand estimates for various conservation uses like irrigation, water supply and hydroelectric power generation. Policy decisions are arrived at introducing the concepts of reliability. In a country such as India where most of the rainfall is concentrated in monsoon months, water demand as ascertained above can generally be met during monsoon period. But for meeting the demand during non-monsoon period a fair idea of the water avilability is required which is based upon amount of water avilable in the reservoir at the end of monsoon period, estimated inflow into the reservoir during the nonmonsoon period and losses from the reservoir. The reservoir operation for the year is then planned based on earlier decided policy. If necessary, allocation for some purposes may have to be curtailed, depending upon relative priorities.

2.2 Operation of flood control reservoirs

The flood control reservoirs can be broadly classified into the categories-ungated and gated. The former type are developed by constructing a dam with ungated spillway. Thus the outflow from these reservoirs is only a function of storage. In a way, the operation policy is built in the structure and cannot be changed without structurally altering it. The other type of these reservoirs, as the name suggests are the gated ones where the spillway is provided with gates. The outflow from these reservoirs can be controlled. In addition to serving for flood control, these reservoirs generally serve conservation demands as well and therefore serve as detention basin. The flood control aspect of these reservoirs is governed by the requirement that as far as possible, no flood water should be released from the reservoir which will cause damages in the downstream reaches. It is possible to find out the operation policy for the reservoir for the design flood or any historic flood for different initial reservoir conditions.

There are two categories of multipurposes reservoirs which have flood control as the main purpose:

a) Reservoirs with permanent allocation of space at the top of conservation pool exclusively for flood control.

b) Reservoirs with seasonal allocation of space for flood control. This space can be used for conservation purposes in other seasons

2.2.1 Permanent Allocation for flood control

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 space exclusively for flood control at the top of conservation pool becomes necessary. In such cases the flood control space is always kept reserved although the space may vary according to the magnitude of floods likely to occur during a particular period and the water is allowed to encroach at this space only during occurrence of floods. 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. Often the allocated space is kept above spillway crest level.

A study of historical or generated floods can indicate the storage space which should be kept reserved during different periods to permit satisfactory regulation of flood flows and thereby develop a plan of allocation of space for flood control during different times.

This space can be used for conservation and other purposes during the periods when floods are unlikely to occur.

2.2.2 Seasonal allocation for flood control

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. The operation plan is prepared based on study of historic or generated floods. There is however no guarantee that the space will be filled every year specially in reservoirs with storage volume forming appreciable part of the annual runoff.

2.3 Operating Schedules and Guides

Schedules and guides for reservoir operation are developed in a preliminary form in the operation planning stage and used to determine, in advance the most effective use of reservoir storage for the various purposes it will serve. These may represent general seasonal guides as well as long range plans for storage and release of water for conservation purposes. In addition rigid or fixed rules may be necessary for operation of reservoir with flood control. The rules are designed to give comparable results in the study of floods of different magnitude and to approximate the levels in the actual operation.

2.3.1 Rigid schedules

Rigid schedules for flood control operation are necessary for use by the operating personnel at gated structures in the event communication with the decision makers fails. Such schedules also serve as guides for operation center personnel during the extreme floods if the communications with reporting hydrologic network is lost.

2.3.2 Semi rigid schedules

The day to day operation of most of the reservoirs is based upon the forecasts of streamflows with such adjustments as may be prudent depending upon the precipitation. Such operation can be more effective in an individual flood event. Use of weather forecasting is made where feasible. These involve day to day operations based on judgements but supported by knowledge gained from studies of past floods. However, if conditions become serious and the flood develops into a maximum probable flood, operation can be shifted to rigid schedules.

2.3.3 Long Range Planning Schedules

Long range planning schedules apply principally to the use of water for conservation purposes and reservoirs where storage is large compared with annual streamflow. Long range planning and scheduling involves distribution of storage and use of water against the long term pattern of streamflow. In a given year an equitable distribution is made for such diverse uses as irrigation, water supply, navigation releases and power generation and storage changes to best carry out the long range potential of the system. Excess flows in a given year are not wasted but are stored for later use to augment the flows during deficient streamflow years which the long range historical records indicate will occur.

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. Mathematically it can be expressed as follows:

$$R_i = S_i + I_i \text{ if } S_i + I_i \leq T \tag{1a}$$

$$T \text{ if } T \leq S_i + I_i \leq T + S_{max} \tag{1b}$$

$$S_i + I_i - S_{max} \text{ if } S_i + I_i \geq T + S_{max} \tag{1c}$$

where, R_i = Release during time period i,

S_i = Storage at the beginning of period i,

I_i = Inflow during period i,

S_{max} = Maximum reservoir storage capacity.

T = Target for release. This policy, although very simple and straightforward, has several drawbacks. The main among them is that at any time when a decision to release water is made, this volume can only be estimated. The uncertainty due to this aspect must be considered explicitly. Further, this operating policy does not consider the past decision; it is a one-time operation policy. This policy is generally not used in day-to-day operation due to its rigidness and above drawbacks. It is, however, extensively used in planning studies.

2.5 Rule Curves

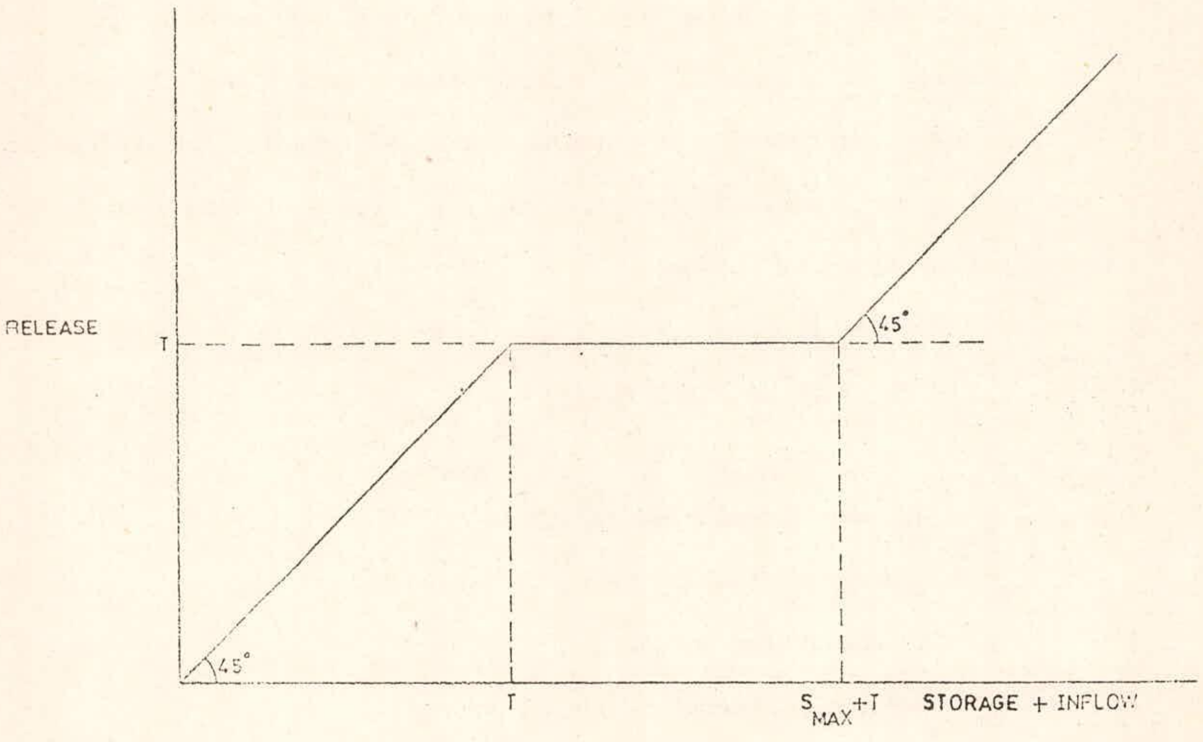

FIG.1 CONVENTIONAL RESERVOIR OPERATION POLICY

A rule curve is a graphical representation specifying ideal storage or 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 purposes if the storage levels or 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. This amount will depend upon the inflows to the reservoir, or sometimes it is specified in addition to rule curves.

The rule curves are generally derived by operation studies using historic or generated flows where long term historic records are not available. Many times due to various conditions like low inflows, minimum requirements for demands etc., it is not possible to stick to the rule with respect to storage levels. It is possible to return to the rule curve in several ways. One can be to return to the rule curve by curtailing the release beyond the minimum required if the deviation is negative or releasing an amount equal to safe carrying capacity if the deviation is positive.

2.6 Derivation of Rule Curves

2.6.1 Reservoir with seasonal storage

First of all, a simple case of a reservoir with seasonal storage serving for conservation needs may be considered. The seasonal storage requires carryover of water from wet to dry season and a reservoir with seasonal storage does not remain full at all times of the year. Further if the reservoir is able to meet the demands during the driest year, it will be able to serve its purpose at all times of the year.

In figure 2(a), the streamflows of a river and the water requirements have been plotted. Let us assume that at time A, the reservoir is full. From A to B, the demands exceed the natural inflow and hence the contents of the reservoir will be depleting. The mass curves of inflows and demands have been plotted in figure 2(b). From time at A onwards, the inflow and demand curves diverge and the difference is maximum at B where it gives the required capacity. Now, in figure 2(b), at point C, the reservoir is empty. From this point, the demand curve is plotted backwards in time and curve CE is obtained which is curve AB lowered and extended to the left. The vertical ordinates between the inflow mass curve EAC and demand mass curve EC represent the volume of water which is in storage at different times of the year. These vertical ordinates have been plotted against time in figure 2(c) and the resulting curve is the rule curve. This rule curve shows the storage requirement at any time of the year. Since it has been assumed earlier that this analysis is being done for the driest year on record and reservoir of adequate capacity, it can be concluded that whenever there is more water in the reservoir than specified by rule curve, there is no danger of subsequent failure of the reservoir.

In a case of multipurpose reservoir with seasonal storage serving for more than one purpose, a common combination of purposes is conservation uses and flood control. The reservoir space at the top of conservation pool is allocated for flood control and the space below it is meant for serving conservation uses of water. The river basins in India typically experience major floods during monsoon months of July, August, Sept, and October. During other months of years, the probability of a major flood hitting the reservoir is

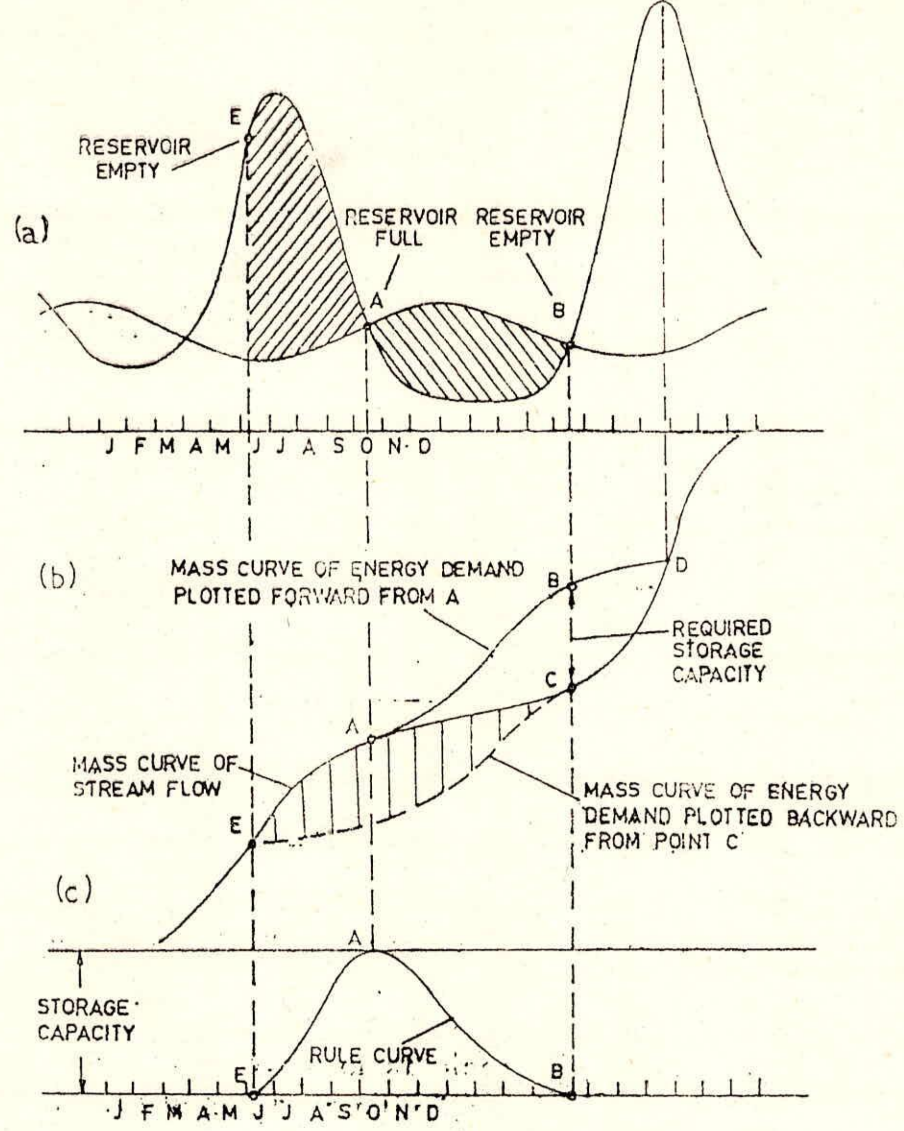

FIG.2 THE STREAMAFLOWS OF A RIVER AND THE WATER REQUIREMENTS

very small or sometimes insignificant. Hence towards the end of monsoon months the empty space above conservation pool is utilised to store water which could be used for meeting conservation demands later on.

In figure 3 annual plans of operation of a multipurpose reservoir where flood control is one of the purpose is shown. It gives the rule curve for reservation for flood control storage during monsoons and non-monsson period and normal operation for conservation purposes for later part of the year.

2.6.2 Reservoir with multi annual storage

Streamflows of a river for the most critical period of record have been plotted in figure (4a) alongwith the hydroenergy and other conservation use requirements. It is seen from the figure that a carry-over storage is required here as the water is carried over from one year to another. The reservoir will be full at time A and thereafter, passing through various stages will become empty at B. The mass curve of streamflows and the hydroelectric energy and other demands are plotted in figure (4b). The ordinate AC represents the required reservoir storage. The ordinate between the mass curve of streamflows and the mass curve of demand represents the amount of water available in the reservoir at that particular time. These ordinates are plotted on a horizontal base in figure (4c). This exercise is done for other critical flow periods to obtain similar type of curves from A to B. Now these curves are screened month by month and the highest deficiency points are chosen. An envelope curve can be drawn using these points which is the required rulecurve. At the time of actual operation if the reservoir is above the rule curve

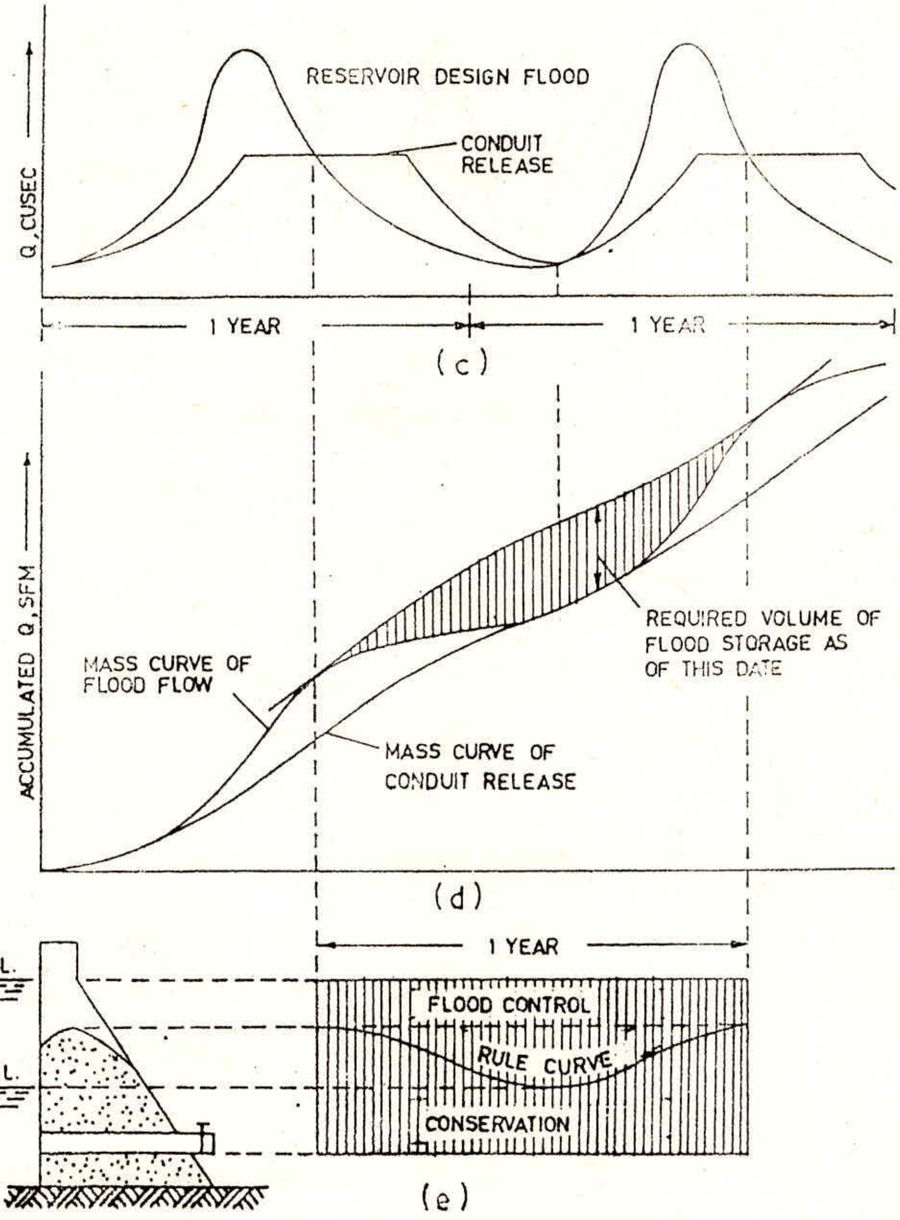

FIG.3 ANNUAL PLANS OF OPERATION OF A MULTIPURPOSE RESERVOIR

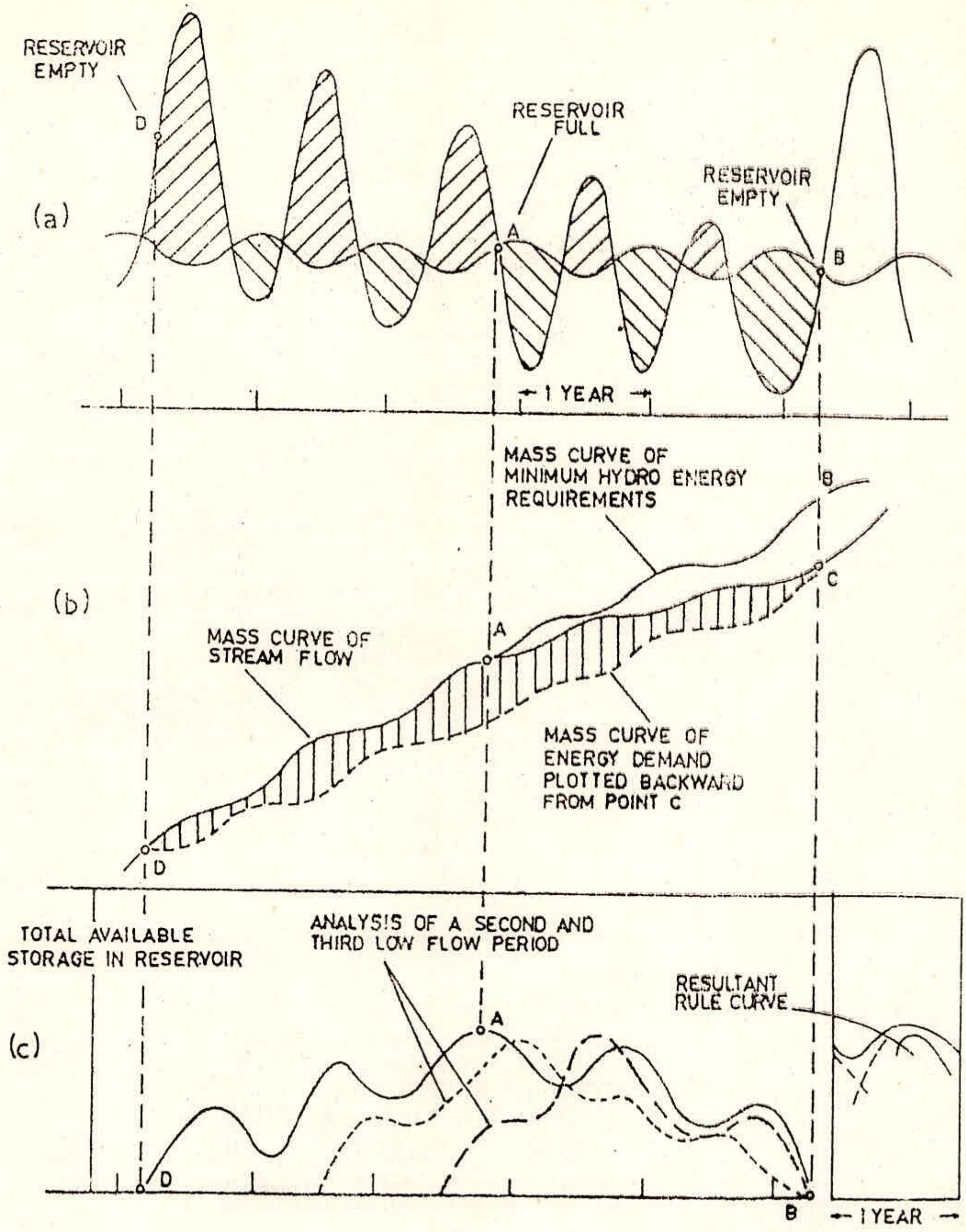

FIG.4 DETERMINATION OF OPERATION RULE FOR A RESERVOIR WITH MULTIANNUAL STORAGE

elevation on any date then all the water which could be used to generate useful energy is released from the reservoir. If the reservoir contents fall below the rule curve elevation, the releases are made to supply the minimum hydro-energy and other requirements and an attempt is made to return to the rule curve as quickly as possible.

The rule curves available for operation of Panchet reservoir located in Damodar valley are shown in figure. 5.

2.7 Flexible operation of reservoir

A reservoir operation schedule for reservoirs with adequate forecasting system for streamflows and precipitation termed as flexible schedule. The reservoir operation decisions are based on analysis of the reservoir system, except in case of probable maximum flood where rigid operation schedule become operative. This flexible operation requires use of better models and careful planning and use of computers. However, the significant amount of larger benefits which can be derived by the flexible schedule makes it imperative to follow them for major reservoirs particularly when the resource availability is limited and allocation has to be done among a number of competing users.

2.8 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 rules governing the maintenance of storage levels in a specified range is based upon the conviction that at a specified time an ideal storage zone exists for a reservoir which when maintained gives maximum expected benefits. This concept is in some way akin to concept of rule curve. Only added advantage

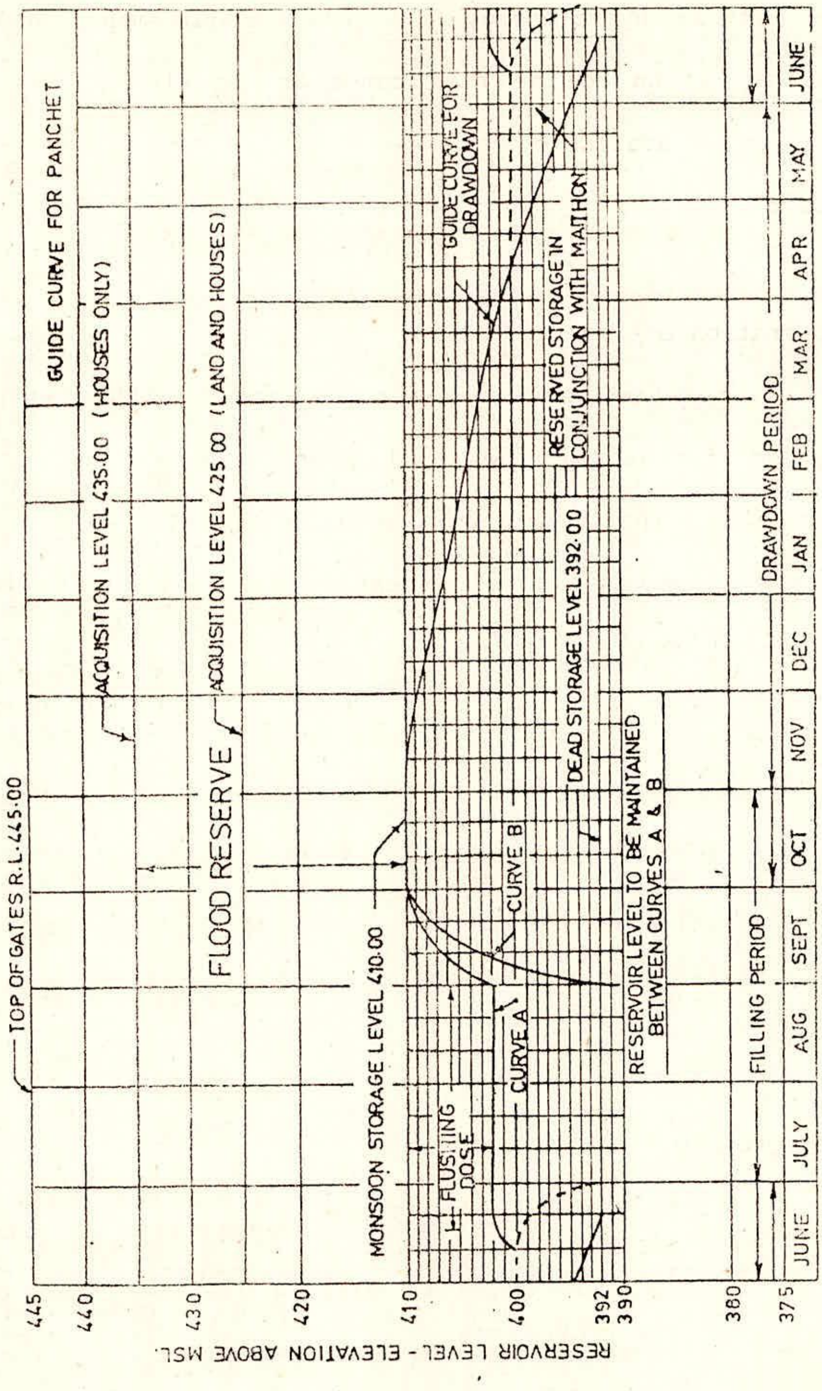

FIG.5 RULE CURVES FOR PANCHET RESERVOIR IN DVC

here is that this approach gives more freedom to the decision maker to fluctuate the level within the specified zone. The degree of freedom depends upon the size of zones into which reservoir is divided.

The zoning concept was systematically presented by Sigvaldason (1976) in the form of a model which was applied to study the operation of Trent river basin projects in Canada. In Sigvaldason's model, the reservoirs were divided in the following five zones which are shown in figure 6.

i) Dead Storage Zone: This zone, also called inactive zone was provided to cater for sediment entering in the reservoir and to maintain minimum required head for turbines. Water from this zone may be withdrawn in exceptionally extreme dry conditions. This is the lowest zone of a reservoir.

(ii) Buffer Zone: This zone, which is located above the dead storage zone is provided to take care of extreme situations and withdrawals from this zone are made to satisfy only very essential needs. As the name suggests, this zone is a buffer between dead zone and conservation zone.

(iii) Conservation Zone: Water is stored in this zone to satisfy future conservation requirements like hydropower, irrigation, and water supply etc. This zone, located above the buffer zone, usually provides the bulk of the storage space.

(iv) Flood control zone: The storage space in this zone is used as temporary storage for alleviating down-stream flood damages during periods of high flows. After the flood has passed, the space is emptied as soon as possible to be ready to negotiate next flood event.

(v) Spill zone: This storage space is situated above the flood cont-

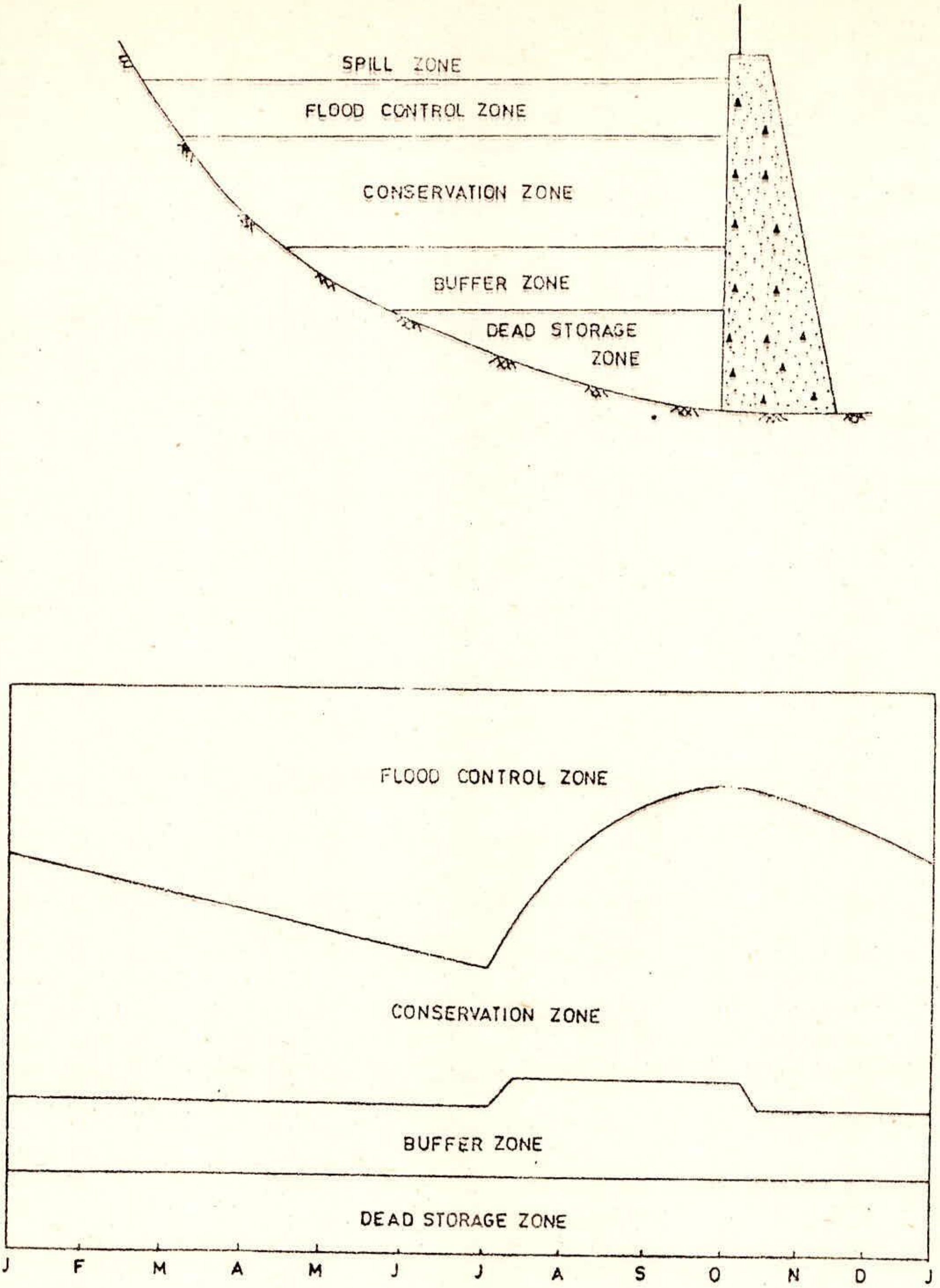

FIG.6 SCHEMATIC REPRESENTATION OF VARIOUS RESERVOIR ZONES

rol zone. This space is occupied only in extreme events and releases from this zone are trade-offs between structural safety and downstream flood damages.

In the model of Sigvaldason (1976), the concept of zone was further supplemented with a rule curve. Once the storage is maintained within the specified zone, the rule curve specifies where exactly it should lie within that zone. The channel flows were also divided in a number of ranges and penalties were levied for deviations from the target. The penalty for unit deviation were different from one zone to other and their relative magnitude governs the decision given by the model.

Sigvaldason (1976) also used the concept of interreservoir zonal operation where all reservoirs were required to operate in the same zone at a particular time. If any violations to this policy occured, the amount of violations was by same margin or same percentage.

3.0 SYSTEM ENGINEERING TECHNIQUES FOR RESERVOIR OPERATION

A system may be defined as a collection of objects with a well defined set of interactions among them. A system may be natural, for example the solar system or man-made, e.g., a reservoir system or a flood control system. The term system engineering vis-a-vis water resources, may be defined as the ensemble of quantitative methods used for defining and evaluating water resources development and management altermatives using a variety of mathematical techniques together with knowledge of hydrology, hydraulics, economics and environmental engineering. Thus the system engineering is concerned with decision making for those systems on which some controls can be applied to best attain the given objective subject to various physical, social, financial and other constrains.

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 for problems associated with reservoir operation are simulation and optimization. These are being discussed in details.

3.1 THE METHOD OF SIMULATION

Simulation can be defined as the process of designing a computerized model of a system or process and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies for the operation of the system. Here the important point to be considered is that simulation is related with the traditional approach of using models for problem solving. However, the type of models has been changed as a consequence of impact of computers but the essence of simulation is to reproduce the behaviour of the system in every important aspect.

At this stage it may be asked as to what is the need of simulation? Although the physical models are in use for a very long time, these are not suitable for analysis of water resources systems. The model building for these systems is a time consuming and costly affair and the testing of say different operating policies is not possible thru these models. Further, complications arise in the physical models in case it is required to evaluate the alternate configurations and sizes of the facilities. In such situations, the mathematical models are most convenient to use.

3.1.1 Time management in simulation

The simulation models are used for studying both static and dynamic systems. Most of the simulation models are dynamic in nature and therefore have a time keeper or a way to depict the change of time in the system. The two common ways of time management are periodic scanning and even scanning. In the periodic scanning or fixed time scanning, the whole computation time is divided into smaller time periods. The simulation clock is incremented by the predetermined step and the system is examined to check whether any event has taken place during this interval. If such events have occurred these are simulated otherwise no action is taken. The clock is again advanced and the procedure is repeated till the end of period of analysis. For example, in case of simulation of operation of a reservoir system, the time horizon of one year may be divided in months. The clock may be initialized to the first month. The events occuring during that month be simulated and then the clock be advanced to next month.

A judicious choice of time increment is necessary in this type of models. This increment should be small enough so that no significant information is lost. But the smaller the time increment, larger will be the amount of computations to complete the simulation which results in added cost for each run. On the other hand, the amount of computations and hence cost will reduce with increase in time of period of computation but there are higher chances that an event of interest may be missed.

In the event scanning approach, the clock is advanced by the amount of time which is required for the occurance of next event. In many natural phenomena, the periods of high activity are separated by long periods in which the system lies inactive. This approach is suitable for this type of situations. It requires some scheme to determine the time when the events take place. Although the computations are substantially reduced in this approach, the models become considerably complex. In case of water resources systems modelling, the fixed time scanning approach is the one which is mostly used.

3.1.2 Consideration of Stochasticity in Simulation

In case of the system where random variable affect the performance of the system, the deterministic simulation may not be able to provide the analyst complete required information. The stochastic simulation is a powerful tool for evaluation of the probability distribution of the performance indices of these type of system. For example, in case of reservoir operation studies, the reservoir may be empty, half filled or fill in the beginning, the streamflow and rainfall are random and so are the demands and therefore stochastic simulation is better suited for these type of problems.

Included in any stochastic simulation model is a provision of generation of random numbers. Mostly computers have a provision to generate random numbers in the range zero to one. Knowing the probability distribution followed by the variable, these numbers can be suitably transformed to yield series of required statistical properties. This series can then be used as input for the purpose of analysis.

3.1.3 Interpretation of Results

The interpretation of simulation output is a very important step in the simulation analysis because it is also very much necessary for proper choice of variables for next steps of computations. Before result interpretation the analyst must specify a performance criterion to evaluate the alternate strategies. The relative effect of various decision variables on the performance of the system should be available on known. This step can be best explained with the help of an example and the text from Loucks et al (1981) is recommended for this purpose.

3.1.4 Limitations of Simulation

The following are the major limitations of simulation techniques.

The simulation analysis does not yield an immediate optimal answer. This technique is most suitable to answer the question-what if? Thus each answer basically pertains to a combination of selected variables. A number of iterations are to be performed to arrived at the optimum. Since in a real life problem, it may not be possible to examine all the related variables at sufficiently close interval, the sampling must be done judiciously.

The second major limitation of simulation is because the models generally lack the flexibility in terms of operating procedures of the system. For example, in a programme dealing with reservoir operation, the criteria as to whether water is to be released from a particular zone and so on is specified in the programme. Any major change in this criteria requires corresponding modifications in the programme and then retesting of the programme.

The third drawback of simulation arises because the historical streamflows are used in simulation. In reality, these streamflows may not be representative for that basin. Moreover, it is quite unlikely that the streamflows will repeat in the same order in future as they did in the past.

3.1.5 Advantages of simulation

The simulation models are best suited to answer the questions of the type what if? A big advantage with simulation is that it allows for controlled experimentation on the problem without causing any disturbance to the real system. Simulation also allows for significant time compression, i.e., the analysis of a system for 10 years may be completed within say, half an hour on a computer. It is very easy to study the sensitivity of different parameter to the inputs. Lastly, though not very relevant to water resources systems, it is also a very good training tool.

A mathematical model is a set of instructions or mathematical relationships which explain the response of the system to inputs. These relations are arranged in a logical order. As an example, suppose that it is desired to develop the reservoir operation policy using simulation. A computer programme is developed which logically transforms the given inflow series into the outflows using the trial operation policy. At the same time benefits or costs are also computed. Once the computer programme is run with the input data, the answer available is as to what happens if the given inflow series were fed into the reservoir which follows the trial operating policy. The different operating policies can be tried and similar results obtained for each. A comparision of the benefits obtained will bring forth the best operating policy.

3.2 Some Generalized Simulation Programmes for Reservoir Operation

A number of general purpose computer programmes are available nowadays which can be used to analyse virtually any configuration and any purpose of a water resources system.

A versatile quasi-simulation model, called SIMYLD-II has been developed by Texas Water Development Board (1972). This model can be used to simulate operation of reservoirs subject to a specified sequence of demands and hydrology.

In the SIMYLD II model, the physical water resource system is transformed into a capacitated network. The conceptual network consists of two components-nodes and links. A node is a connection and/or branching point within the network and is analogous to a reservoir or non-storage junction in the physical system. A node has the capacity to store a finite and bounded quantity of water and can serve as a branching point. Thus a diversion can be treated as a node point whose storage capacity is zero. Any water which enters the system does so at the nodes only and all the demands are assumed to be placed at the node points.

The water is transferred from one node to another by the links. Thus a link may represent a river reach, canal or a pipe of the physical system. Each link has a specified flow direction and maximum carrying capacity. A minimum carrying capacity may also be associated with each link to represent requirements of minimum flow along the corresponding element.

As input to the model, the user is required to supply priorities between meeting demands and satisfying final end of month storage requirements in the reservoirs. The priorities are converted into cost in the model. Those related with demand and desired storage are assigned negative costs or benefits; more negative is the number ,higher is the priority for meeting the upper constraint. Physical system link and spill costs, are positive costs. The idea is to meet targets of demands and desired storages in order of the priorities while minimizing the canal pumping and spill from the system.

The optimal allocation of network flows is accomplished by using the 'Out-of-Kilter' algorithm. This is an optimization algorithm which finds the minimum total cost of water circulation within the net-work subject to flow constrains. If q_{ij} is the amount of water flowing from node i to node j and C_{ij} is unit cost of moving water from node i to node j then the objective function is to minimize $\Sigma C_{ij} q_{ij}$ for all i and j. In out-of-Kilter algorithm, it is required that the objective function and the constraints must be linear in nature.

To provide flexibility in operation, the SIMYLD II model allows for three sets of operating policies depending upon the hydrologic state of the system. The three hydrologic states typically are, wet, average and dry. Thus the user can specify different set of priorities of maintaining a particular storage and meeting demands corresponding to the hydrologic state of the system.

Two generalized computer programmes developed by the Hydrologic Engineering Center (HEC) of US Army Corps of Engineers are extensively used for simulation of reservoir systems. These are being discussed here briefly.

The programme 'Reservoir System Analysis', HEC-3 has been developed for simulation of operation of a reservoir system for conservation purposes such as water supply, irrigation, hydroelectric power generation, navigation and low flow augmentation. The system consists of a number of control points linked with each other. Reservoirs are control points which have a finite amount of storage associated with them. The operating criteria of a reservoir has to be supplied. Each reservoir is operated to meet the streamflow targets at specified locations in the system. To do this, each reservoir is divided into a number of zones by imaginary horizontal planes and withdrawls are made from the highest zone first and so on. As far as possible, all reservoirs in the system are kept in balance.

The system is operated by considering the requirements at pertinent control points in the system, starting at the most upstream control point and moving in the downstream direction. The required release is determined by evaluating all operational needs and other constraints. After the requirements have been made or shortage declared, the system requirements are examined to determine additional releases which may be required to meet the system power demands. If these releases are required then they are proportioned among the projects which are supposed to cater for them. These additional releases are added to obtain the total releases. This process is repeated for each period. The hydrologic accounting is done by use of continuity equation at each control point.

The various features of this programme have been described in detail in the users manual for this programme, HEC(1974). This manual also describes the input and output of the programme for various test problems.

Another HEC programme for surface water systems analysis is the HEC-5, Simulation of Flood Control and Conservation System. This programme is considerably more versatile than HEC-3 and can be used to analyse a system for both flood control and conservation purposes. It has been designed to simulate the operation of multipurpose multi-reservoir systems. Virtually any complex reservoir system may be simulated to meet practically any demand for water including water supply for municipal and industrial uses, irrigation, hydroelectric power generation, navigation or other conservation demands and flood control demands.

As in HEC-5, the storage in reservoirs is divided into a number of zones by conceptual horizontal planes. The size of these zones may vary from month to month. Typically a reservoir is divided in inactive zone, buffer zone, conservation zone and flood control zone. Except flood control zone, all other zones are used to cater for the conservation demands except the inactive pool from which no releases are made. The flood control zone is used during the high flow periods and the releases are made such that the downstream channel capacity is not exceeded. The determination of release is made by calculating the release required to exactly fill the carrying capacity for each time period of forecast at each affected control point and the adopted release is the minimum of these for flood control operation and maximum for conservation operation. The programme has a provision for limitations on the rate of change of release which can be specified by the user.

The details of this programme including theoretical aspects, description of input and output, sample runs and application procedures are described in detail in HEC(1982) and Feldman (1981).

3.3 Optimization Techniques

Optimization is the science of choosing the best solution from a number of possible alternatives. In many engineering problems, a typical situation arises in which there are many ways of achieving a particular objective. For example a number of release decisions may be available to cater for irrigation and hydroelectric power, a number of alternative designs may be available to serve the municipal water demands, and a number of management decisions may be available to increase the production. Naturally, the result attained in each case will be different and it is required to choose the best from the point of view of interest, say economical, physical or convenience.

The complexity of the optimization problems depends upon the number of factors affecting a particular choice. For simple problems, the analysis can be performed manually but the computations become manually unmanageable when the number of interacting factors become large and the optimum choice in such cases is to use a digital computer.

Mathematically, an optimization problem can be stated as:

Find $X = [\ x_1\ x_2\ \ldots\ldots x_n]^T$

which optimizes $f(X)$

subject to the constraints

$$g_j(X) > b_j,\ j = 1,2,\ldots\ldots m \qquad \ldots(5)$$

and $$l_j(X) = b_j,\ j = m+1,\ m+2\ \ldots\ldots,p \qquad \ldots(6)$$

where

X = a n-dimensional vector of decision variables

$f(X)$ = objective function,

$g_j(X)$ = inequality constraints, and

$l_j(X)$ = equality constraints.

The decision vector represents the variables to be manipulated to obtain the solution. As an example, release from storage is a decision variable in a reservoir operation problem. The decision variables are choosen such that the decision maker's objective, $f(X)$, is optimized. The objective function either represents benefits which are maximized or it represents costs which are minimized. It can be easily seen that maximization of a function is analogous to minimization of its negative. In a reservoir operation problem, the aim may be to maximize the benefits by deciding the amount of water to be released. But in many cases it may not be possible to release a particular amount of water because of limited capacity of outlet structures or because that much water may not be available. In other words, the decision variable is forced to take a value within a specified range. If this case when the problem is said to be constrained. It may happen that constraints may force a decision variable to have value less than a specified upper limit (say release restriction becuase of limited capacity of outlet works), or they may force it to have value greater than a lower limit (say a binding that release must always be greater than a minimum value) or both. These types of constraints are known as inequality constraints since the left hand side and right hand side of the constraints need not be equal. Sometimes the condition of equality has to be satisfied. For example, continuity equation which specifies that the initial storage plus inflow minus releases and losses must be equal to the end-of-period storage appears as equality constraint in many problems.

A solution of the optimization problem which satisfied all constraints is called a feasible solution. A feasible solution, however, may or may not be optimum. If no further improvement to a feasible solution is possible, the solution is called optimum solution. If it is not possible to get any feasible solution, the problem is termed infeasible. Further, it may happen that more than one combination of decision variables may give same value of objective function which may also be the best value, in such cases all the solutions are called alternative optimum.

The optimization methods try to find out a set of decision variables such that the objective function is optimized (i.e.,either maximized or minimized). Due to the very nature of these models, they are very much helpful in initial screening of alternatives. The models become particularly helpful in studying the operation strategies of reservoirs. The decision making choice can be explicitly expressed through objective function. Versatile programs can be written which can take widely varying nature of objective functions. Only a single run of the program is required to obtain the optimal solution. Post optimality analysis, also called sensitivity analysis is an important and useful part of an optimization model. In this analysis it can be determined as to how much sensitive an optimal solution is to the changes in the value of decision variables and how it changes by loosening or tightening of a particular constraint by a given amount.

3.3.1 Choice of Objective Function

The choice of objective function is a very important decision in an optimization formulation. In the operation of a reservoir, a large number of alternatives are available to the decision maker. The output from each alternative must be measured in terms of a common unit. To choose a particular alternative, it is necessary to rank the alternatives in terms of attainment of the objective. The criterian used in this ordering or ranking is called the objective function.

Starting with the main objective of water resource development as increasing national income, Maass et al (1962) introduced the notion of economic efficiency. According to them, a project will be called economically efficient if no alternative design would make any member of the community better off without making others worse off. To evaluate the economic efficiency, they introduced the willingness-to-pay criteria.

The willingness of the people, affected by a particular project, to pay for it in terms of zero deisgn (i.e,no project at all) can be measured and can be used to rank the projects. However, these types of criteria can be useful only in the design stage to screen the alternatives and are not helpful in the operation stage of a project. Nevertheless, it can be shown that all the objectives are reducible to economic efficiency objective.

In spite of the importance of choice of objective function for a problem, detailed guidelines are not available for its selection for a particular problem. Usually, the choice of the objective function is governed by the nature of the problem and also the computational facilities available. Many times a linear objective function is choosen because it reduces the computational efforts significantly and moreover, efficient computer programs are widely available for linear programming problems. One way of converting nonlinear objective function to a linear one is piecewise linearization. In this approach, the function is divided into a number of segments such that it behaves linearly in each segment. The number of such segments depends upon the nature of objective function, permitted distortions as a result of this process and also the computational facility (e.g.time and finances) available. A finer division will, no doubt be more precise but will require more processor time.

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 to minimize the flows which are greater than the safe carrying capacity of the channel. Similarly, 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.

For a long term operation problem, the aim is more to fix the targets or the maximum attainable level of power or water. This may typically be in the form of maximization of firm power or firm water.

3.4 Applications of Optimization Techniques to Reservoir Operation

A large number of studies using optimization have been conducted on reservoir operation problems. The reasons for this proliferation of studies are very clear. More stringent demand are being placed by society on existing water resources which require better management for higher degree of satisficing.

Out of various optimization techniques discussed, two have been most commonly used for reservoir operation problems. These are linear programming and dynamic programming. Dynamic programming has been extensively used in cases where the objective function is nonlinear or for stochastic optimization problems The user of integer programming is mostly for capacity expansion problems. Stochastic programming in conjunction with LP or DP has also been widely used. For the purpose of this manual the discussion is limited to linear programming and dynamic programming techniques as only these two are used in practice.

3.4.1 Linear Programming Techniques

The applications of linear programming to reservoir operation have been far and wide. First of all, a simple problem formulation is presented here.

Let us consider that a reservoir located at a particular site supplies irrigation water to a nearby agricultural area. The dead storage capacity of the reservoir is S_{min} and the maximum capacity is S_{max}. For the most critical year in past, monthly inflow data are available and it is required to find out the releases to be made from the reservoir each month to maximize the benefits. The monthly distribution of the water demand is available, i.e., if the annual demand is X than its distribution among 12 months $\alpha_1 X, \alpha_2 X, \alpha_3 X \dots \alpha_{12} X$ is known.

If the water released for the i^{th} mouth is R_i than for nonfailure operation of the reservoir, it is essential that this release must be greater than or equal to demand $\alpha_i X$ for that month. This can be expressed mathematically as

$$R_i \geq \alpha_i X \qquad \dots(7)$$

This condition must be satisfied for every month. Hence there will be 12 such constraints.

$$R_i \geq \alpha_i X \qquad i = 1, \ldots 12 \qquad \ldots(8)$$

If the storage in any month is represented by S_i and inflow by I_i then according to continuity equation, the sum of initial storage and inflow for the i^{th} month less release during that month will be equal to the initial storage for next month. All losses are being ignored for the sake of simplicity in the present example. Further, there will be twelve such constraints, i.e.,

$$S_i + I_i - R_i = S_{i+1} \qquad i=1, \ldots, 12 \qquad \ldots(9)$$

Apart from these constraints, from the physical point of view, the storage cannot exceed the maximum storage any time. This will also give rise to twelve constraints of the form

$$S_i \leq S_{max} \qquad i = 1, \ldots 12 \qquad \ldots(10)$$

Similarly, it must also be ensured that the storage never falls below the minimum permissible value, or

$$S_i \geq S_{min} \qquad i=1, \ldots 12 \qquad \ldots(11)$$

The important thing left is the design of objective function. As the aim here is to maximize the benefits which are assumed to be linear function of release, it can be put as

$$\text{Max } Z = \sum_{i=1}^{12} f_i (R_i) \qquad \ldots(12)$$

The entire problem can be put here as

$$\text{Max } Z = \sum_{i=1}^{12} f_i (R_i) \qquad \ldots(13)$$

Subject to

$$R_i \geq \alpha_i X \qquad i=1, \ldots 12.$$

$$S_i + I_i - R_i = S_{i+1} \qquad i=1, \ldots 12$$

$$S_i \leq S_{max} \qquad i=1, \ldots 12$$

$$S_i \geq S_{min} \qquad i=1, \ldots 12$$

$$R_i \geq 0 \qquad i=1, \ldots 12$$

The problem has 48 constraints. It can be easily solved using a standard LP package. The solution will give the optimum value of release for each month.

It may also be mentioned that all the losses have been ignored in the present example. If evaporation losses are to be considered then the area capacity curve has to be used which is not linear in nature. One way out is to divide this curve in a number of segments and then linearize it in between two segments. This process is known as piecewise linearization. The accuracy depends upon the number of segments into which the entire region is divided.

In this example, only one year of data (12 months), was used. However, in practice this may never be the case. Thus, for example, if data of 10 years are used then the number of constraints will increase to 480. This undoubtedly is a large number and it increases rapidly as the number of years is increased. If the analysis is carried using yearly data rather than monthly then the number of constraints will sharply reduce but this is not very much advisable. One remedy is to explicitly treat the stochasticity of the inflows by using the technique of stochastic linear programming. In this technique, an appropriate probability distribution is assumed (or fit) for the inflows. A particular reliability level is adopted and in the continuity equation, that particular value of inflow is used which is exceeded with specified probability. The modified continuity constraint is written as

$$S_i + I_i(p) - R_i = S_{i+1} \quad i = 1, \ldots 12 \qquad \ldots(15)$$

where $I_i(p)$ is the inflow value which is exceeded with a probability of p in the month i. This formulation will reduce the number of constraints to 48 with the added advantage that the stochasticity of inflows has been taken into account. Further, the sensitivity of the reliability parameter can also be studied.

This formulation, although convenient to use, has been severely criticised. The main criticism is about the implicit assumption that the critical flow will occur in each month of the critical year. This assumption is not true in reality and it leads to conservative values.

After explaining a simple formulation of the problem in linear programming framework, the attention is now focussed on some applications of this technique Among the first reported works using linear programming, the study carried out in the Harward water program is probably most significant. In this study, as reported by Maass et al (1962), a stochastic LP technique was used to find out the optimal reservoir operating policy. The formulation was as follows:

The total inflow to a reservoir in a given period was assumed to be a stochastic variate. It is known that as the inflow is discretized in finer or smaller units, better representation of the actual condition is achieved. A too fine discretization will, however, significantly increase the amount of computations. Similar arguments hold good while deciding about the number of time periods in which a year is divided for computational purposes. The number of time periods should be such that the streamflow and demand pattern is faithfully reproduced at no significant increase in the cost of computations.

In the above model, the initial state of the system was defined using two variables-inflow and storage. It was assumed that there is no serial correlation between the inflows in succeeding periods. The constraints included the continuity equations (one for each period) and constraints for limiting storage to the maximum reservoir capacity in each period. The decision variable for the problem was draft to be permitted from storage so that the expected value of benefit may be maximized. The objective function was to maximize the expected value of benefits over entire operating horizon, for all values of storage and release. The consistency of LP solution was checked using queueing theory.

Although this study was very successful, it had some limitations. The model developed could be used only to study operation of a single reservoir. Multiple purposes could be explored only if they could be combined into a single objective function. Serial correlation between inflows was also not permitted. The number of time periods was restricted to computer memory capacity which was quite small in those times. The computation of hydroelectric power benefits poses a problem in LP models. In the above model, it was assumed that the energy output is a function of end-of-the period storage and water released. If the analysis had to be done for flood control, the assumption was that average flows and flood damages have a good correlation. The computations for the above model, which was applied to a hypothetical basin, were performed on a IBM 700 computer.

The most important and yet most controversial application of the LP to problems of reservoir system has been in the framework of Linear Decision Rule (LDR). This rule, which was originally proposed by ReVelle et.al(1969), can easily be applied both in deterministic and stochastic framework. In the LDR, it is assumed that the release is a linear function of storage, or

$$R_t = S_{t-1} - b_t \qquad \ldots(16)$$

where R_t is the release during time period t, S_{t-1} is the storage at the end of period $(t-1)$ and b_t is the decision rule parameter which optimizes the chosen objective function. The problem posed by ReVelle et al (1969) was to find the smallest reservoir which will deliver required flows under the physical constraints and equation (16). Rules, such as power rule or fractional rule may perform better than LDR but the additional computational burden may not be worth while. The authors presented LDR in deterministic as well as chance constrained formulation. In the chance-constrained formulation, flows are known only with attached probability. Similarly, the constraints also have probability values attached with them. They may be present to ensure that (i) the release must exceed a minimum value with a specified probability, (ii) the release must not exceed a maximum value with a specified probability, (iii) the storage must not go below a particular value with a specified possibility, and (iv) a minimum amount of freeboard must be available with a specified probability. Since its introduction, the LDR has been modified to consider evaporation losses, hydro-electric power benefits and extended for multi reservoir systems.

ReVelle and Gundelach (1975) presented a new LDR in which release is a function of current storage as well as past inflows:

$$R_t = S_{t-1} + B_t I_t + B_{t-1} I_{t-1} \ldots . B_{t-k} I_{t-k} + b_t \qquad \ldots (17)$$

where B_t, $B_{t-1} \ldots . B_{t-k}$ are constants to be determined. The authors pointed out that this form of LDR permits a smaller reservoir capacity than the original LDR. They used the condition of minimum variance of release to determine B weights.

Loucks and Dorfman (1975) pointed out that the LDR models give conservative results. The reason is that these models assume that critical flow and critical storage simultaneously occur in each period. In practice, their joint probability is negligible and this too depends upon the stochastic structure of the streamflows. They presented a

LDR of the form:

$$R_t = S_t + \alpha_t I_t - b_t \qquad \ldots(18)$$

$$0 \leq \alpha_t \leq 1$$

where α_t is a coefficient. The choice $\alpha_t = 1$ gives the least conservative result while $\alpha_t = 0$ gives most conservative result.

Houck (1979) pointed out that the conservative nature of the LDR can be tackled by using conditioned cumulative streamflow distribution functions in the model. He presented multiple linear decision rule in which the release were conditioned on the previous two seasons' streamflows and the storages on the streamflow of two previous months. The model can be easily formulated in other ways also choosing the number of events on which the releases and storages are to be conditioned by considering the accuracy of future streamflow predictions, modelling approximations, and available computational facilities.

In another framework of LDR, presented by Houck et al (1980), the hydroelectric energy generation and economic efficiency benefits were incorporated in the model. The economic efficiency was incorporated in their model as follows. The deterministic constraints, such as for storage and release which are bounded between upper and lower limits, were replaced by chance constraints for particular reliability level . It was assumed that the targets represent long term benefits and the deviations represent short term losses. If a large number of probability levels are chosen such that they represent entire range from zero to one, the cumulative distribution function of deviations can be found out. In a flood control benefit case, the target free board represents the long term benefits. Further, the maximum possible freeboard equals the reservoir capacity and the minimum is zero. In objective function, the expected flood control benefits can be expressed as a function of the target, the probability level and the excess and deficit. As the long term benefit functions are concave and short term loss functions are convex, they can be easily incorporated in the model. In case of hydroelectric power generation, the production function is nonlinear. It was assumed that the reservoir is operated such that during a time period, the volume remains within a small region with high probability. The relationship between storage and head was assumed linear within this small region. The values of expected head and release were used in the benefit function.

Loucks (1968) developed a stochastic linear programming model for a single reservoir optimization. The net inflows to the reservoir were assumed to follow a first order Markov chain. The first order transition probabilities were computed by observing the number of times the net inflow equalled j in period (t+1) after having been i in the period t, divided by the total number of transitions from i to all inflows j. These transition probabilities, when coupled with the reservoir operation policy, determine the probabilities of the transition of the storage volume to another. The objective function was minimization of sum of the expected squared deviations from the target reservoir volumes or discharges.

Mathematically the objective function was

$$\text{Min} \sum_{v,i,d,t} \alpha_t (v-v_t)^2 + (1-\alpha_t)(d-\sigma_t)^2 \, x_{vidt} \qquad \ldots(19)$$

where v_t and σ_t are target initial reservoir volume and discharges in period t, x_{vidt} is joint probability of beginning with a reservoir volume v, having an inflow i and discharging d in period t, α_t is a weighting factor expressing priority of reservoir volume to reservoir release in period t, such that $0 < \alpha_t < 1$. Since x represents probabilities

$$\sum_{v,i,d} X_{v,i,d,t} = 1 \quad \text{for all } t \qquad ,\ldots(20)$$

The probability distributions of the resulting actual reservoir volumes and releases were obtained as solution in addition to optimal operating policies.

3.4.2 Solving Linear Programming Problems

After a problem has been formulated in linear programming frame work, it can be easily solved using a linear programming code. The problem has to be first put in the standard form as given in equation 5 and 6. Nowadays, a large number of standard LP packages are available which can be readily used. The technique which is used to solve a linear programming problem in the Simplex method developed by Dantzig. Hand calculations using Simplex method are possible only for small sized problems. For the real-life problems, hand calculations tend to become unmanageable and computer is almost always used for solving such problems.

3.4.3 Dynamic Programming Techniques

The dynamic programming is an optimization technique based on multistage decision process in which the decisions are taken in stages Basically, it is an enumerating technique which was developed by Bellman in 1953. The technique is based upon the Bellman's principle of optimality which states that if an optimal path is available which joins two points separated in space or time then a portion of this path from an intermediate point to the end point will be the optimal path from that point to the end point. The proof of this theorem can be obtained by contradiction.

Three types of variables are used in dynamic programming formulation:

a) State variables which define the condition of the system.

b) Control variables or decision variables which represent the controls applied on the system and transform the state variables, and

c) Stage variables which define the order in which events occur in the system.

For a reservoir operation problem, the amount of water available in storage at any time is the typical choice of stage variable, the releases made from the reservoir are the control variables because they change the state of the reservoir and time is a natural choice of stage variable. The dynamic behaviour of the system equation can be written as :

$$s(t+1) = f[s(t),\ u(t),\ t],\ t = 1, 2, \ldots\ldots n \quad \ldots.(2)$$

Where s(t) is the state variable at stage t,

u(t) is the control variable applied at time instant t, for a duration dt, t being the length of time in which stage variable is discretized.

Associated with every state transformation is a return which may either represent benefits or costs. The state of a reservoir is transformed by releasing water from it. This water can be used for a number of purposes like irrigation, hydroelectric or municipal water supply. Associated with each use will be certain benefits.

For example, price of the electric energy generated is a measure of benefit from this use. The objective of the best operating decision is to decide about the release in such a fashion that the benefits are maximized. A set of decisions is called a policy. By varying the decisions, a large number of policies can be obtained. Among all feasible policies, that particular one which optimizes the objective function is called the optimal policy.

Let $f_t(s_i)$ be the objective function which represents the net cumulative returns (which may be either benefits or costs) at the end of stage t given that the system is in state i at the start of this stage. The recursive relationship can be written as :

$$f_t(s_i) = \underset{k}{\text{opt}} \left[u_{t,k} + f_{t-1}(s_j) \right] \qquad (21)$$

$$t = 1,2 \ldots\ldots\ldots$$

Where $u_{t,k}$ reprepents the returns obtained at stage t as a result of a decision k. The aim is to find the value of k which optimizes $f_t(s_i)$. Beginning from the first stage, the calculations are carried till the last stage in the forward algorithm of dynamic programming. At the final stage search is made among all allowable stages, to find that particular stage which has optimum returns. Now a backward trace is made to locate the path and decisions which have led to this stage. The path followed by state variable is known as the state trajectory. Alternative to forward algorithm, the computation can be commenced at the last stage and carried backwards to the first stage. This is known as backward algorithm.

The dynamic programming can be easily applied to both linear as well as nonlinear objective functions and constraints. One major advantage in using dynamic programming is that the policy space need not be convex.

As mentioned earlier, while formulating the reservoir operation problem in dynamic programming framework, the storage in reservoir can be taken as state variable, the release from the reservoir as decision variable and the time as the control variable. Knowing the benefit or cost function the recursive equation can be established. But while solving this problem using the traditional dynamic programming computations, a trouble arises which is termed as the 'curse of dimensionality'. This occurs because to obtain sufficiently accurate results,the various involved variables have to be discretized into small intervals and the number of computational results to be stored exceeds the memory capacity of available computers. Among the techniques developed to overcome this problem the Discrete Differential Dynamic Programming (DDDP) is most suitable for reservoir operation problems This technique was proposed by Heidari et al (1971). The DDDP is an iterative procedure in which the recursive equation of dynamic programming is solved within a restricted set of quantized values of the state variables. The initial solution to the problem is assumed known. The optimal solution is obtained by gradually improving the initial solution . The DDDP technique is particularly suitable for invertible systems. A system is called invertible if for that system, the order of the state vector is equal to the order of the control vector. Thus the knowledge of state variables enables one to compute the decision variables. The water resources systems are mostly invertible. For example assuming that the inflows to a reservoir are known, the releases from it can be determined if the states of the reservoir at different times are known.

The DDDP computations start with either a known state trajectory or a known policy. Because of the property of invertibility, the knowledge of one variable enables the determination of the other. The initial values must always satisfy the constraints. Now a set of incremental values of state variable is assumed. When these incremental values are added and subtracted from the trial trajectory at a particular stage, a subdomain is formed around the trial trajectory. This subdomain is called a corridor. At this stage optimization is performed constrained to this corridor and a better value of the trajectory is obtained which is considered as the trial trajectory for next iteration. The computations are performed by varying the composition of the corridor in such a way that the algorithm converges towards the optimal solution.

In most formulations, trial trajectory lies at the center of the corridor though this is not a necessary condition. More than one quantized states on either side of the trajectory may be chosen but the choice of three quantized states at each stage is most suitable for computational efficiency.

To obtain good convergence, two criterion were suggested by Hall (1969). These are guidelines about the increments to the state vector. The first is that the increments to the state variables must be kept small and constant throughout any iteration. The second is that the size of increments should be reduced as the iterations proceed. However, the size of increments should be chosen such that entire feasible region could be inspected if required. There is a strong correlation between the number of iterations required for good convergence and the size of increments at each iteration. It was also suggested by Yeh (1982) that several iterations with a small increment should be allowed at the end of each computation cycle to improve the value of objective function. A computer programme for solving reservoir operation problem is available in Jain (1986). A generalized dynamic programming package called CSUDP was developed at Colorado State University (CSU) by Labadie, Shafer and Fontane (1982). It can be used to solve one or multi dimensional deterministic or stochastic DP problems. Both forward and backward algorithm are available. The CSDUP can also be used to solve the problems having either invertible or non-invertible state equations. However, if state variable is multi-dimensional, only invertible deterministic formulations are allowed. The system equation which represents the transition of state due to application of controls is given by a user supplied subroutine. Similarly, the objective function is also calculated by a user supplied subroutine. The programme also has several options for changing the default values of tolerance parameters and the levels of output.

3.4.4 Incorporation of Stochasticity in Dynamic Programming

The dynamic programming formulation explained in the previous section is a deterministic optimization since the stochasticity of the inflows was not considered. However, the deterministic models are often inadequate given the uncertainties of precipitation, inflow, demand and other associated variables which greatly influence the optimality of a particular decision. This necessitates incorporation of stochasticity of random elements.

Similar to the queues described above, the storage in a reservoir may also be assumed to be analogous to a queue. The inflow to the reservoir may be treated as analogous to the arrival rate of a queue, the outflow as departure rate and the release rules are similar to the service functions.

Another decision making technique which is used in hydrology is the Baye's theorem. This theorem can be mathematically stated as:

$$P_1(a_i/x) = \frac{P_o(a_i)P_r\ (x/a_i)}{\sum_{i=1}^{k} P_o(a_i)\ Pr\ (x/a_i)} \qquad (22)$$

where a_i, i=1, ...k denote all possible states of the system, x is a sample of data, P_o (a_i) are the prior probabilities before receipt of data P_r (x/a_i) are the conditional probabilities of the sample x subject to a_i and P_i (a_1/x) are the posterior probabilities of the states a_i given x.

The above equation states that the posterior probability of a state a_i conditional to a sample x is the joint probability of a_i and x divided by marginal probability of x. The estimate of posterior distribution enable the inference on the state of nature through some parameters specifying it. Some investigators have objected the use of Bayesian theorem in that the prior distributions are either unknown or not easily obtained. Kottegoda (1980) has demonstrated the use of Baye's theorem for reservoir operation problems. The operation research techniques are described in detail in such Texts as Taha (1976), Wagner (1977) and Rao (1979).

The uncertainty can affect both the objective function and constraints. The uncertainty in constraints can be considered by use of chance constrained formulation as explained in the linear programming formulation. The uncertainty which affects the objective function of a problem arises from the imprecise knopwledge of future benefits or costs which may result from alternate decisions. These type of uncertainties can be statisfactorily handled by substitution of the expected value of net benefits in place of just net benefits. In case of dynamic programming, this is not a difficult task.

Let us assume that the system can be in any one of m discrete feasible states, $s_1, s_2, \ldots\ldots s_m$ at any stage. Further, let $P_{ij}^{t}[k]$ be the probability that system is in state s_j in period (t+1), given that the system in period t is s_i and decision k is made. Mathematically, $P_{ij}^{t}[k] = \text{Prob}\,[\,S_{t+1} = s^{j} / S_t = s_i,\ \text{decision } k\,]$ .....(23)

These probabilities are nothing but transition probabilities of a time-dependent decision-dependent Markov chain. The incorporation of these transition probabilities in the recurrence equation leads to new recurrence equation as

$$f_t\,(s_i) = \underset{k}{\text{opt}}\ \left[\ \sum_{j=1}^{m}\ F_{ij}^{t}(k)\quad u_{t,k} + f_{t+1}\,(s_j)\right] \qquad .....(24)$$

Thus at each step t, it is necessary to calculate the expected net benefit resulting from each decision. Apart from this, rest computations are same, which can be carried out using the backward algorithm of dynamic programming. The dynamic programming in Markov chains is discussed in detail in text books like Taha (1971), Loucks (1981).

3.5 Other operations Research Techniques

Besides optimization and simulation, there are some other operation research techniques which have been used for reservoir operation problems.

One such technique is the queueing theory. It was first applied by Langbein (1958) in a comprehensive way. The queueing problems basically arise at a service facility where customers come. Upon arrival at the facility, the customers may be either served immediately if a server is available or he may have to wait (if willing) until a server becomes free. The time taken to serve a customer may be fixed or may vary randomly if the nature of services varies. These situations arise in everyone's day-to-day life. A typical example is the railway reservation counter. Because of involvement of a randomness in arrival or service pattern, it is difficult to optimize such systems. However, the probability distributions of arrival and departure of the customers can be developed. The arrivals are represented by using the interarrival time which is the time lag between arrival of two successive customers and the interdeparture time which is the time between departure of two successive customers.

At the facility, there may be only one server in which case the model is called single server model or there may be more than one server in which case the model is called a multiserver model. The service discipline of a queue defines the order in which customers are selected from a queue. Most commonly, the first-come-first-served strategy is followed. This may, however, be supplemented by special rules, say pre-ferential service for ladies or handicapped persons.

3.6 Real - time operation :

The term real-time operation denotes the operation mode in which the operating decisions are taken based on status of the system at that instant. Additional information available as forecast of future inputs may also be made use of. The necessity for real-time operation arises from the fact that the inflows to reservoirs are random in nature and hence are uncertain. The computations are performed in the following manner.

First of all, it is necessary to develop a mathematical model of the system. This model is generally an optimization model. The release from the reservoir may be taken as decision variable. A forecasting algorithm is also used which provides 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. The basic idea is same as adaptive control in which the decisions are repeatedly updated using the latest available information. This type of control is especially suited for reservoir operation during floods where the system response changes very fast and decisions have to be taken quickly and adapted frequently.

4.0 CONCLUSIONS

The operation of reservoirs is one of the most important aspect of water resources management. The complexity of the problem arises mainly because of future uncertainty and the conflicting nature of demands placed on the reservoir. The types of conflicts which may arise in the operation of a reservoir have been discussed in detail alongwith the functional requirements for various uses of water. The conventional methods of reservoir operation which are based on rule curves have been discussed in sufficient details.

The system engineering techniques are becoming more and more popular day-by-day, particularly with wider availability of computers. Two of these techniques which are very extensively used in water resources systems namely, simulation and optimization have been described alongwith discussions on some generalized computer models available for analysis of water resources systems using these techniques.

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