INTRODUCTION TO RESERVOIR OPERATION

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1. INTRODUCTION

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

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

Once the structured facilities like dams, barrages, hydropower plants etc. come into being, the benefits that could be reaped depend to a large extent upon how these facilities are managed. The efficient use of water resources requires not only judicious design but also proper management after construction. Reservoir operation forms a very important part of planning and management of water resources system. Once a reservoir has been developed, detailed guidelines are to be given to the operator which enable him to take appropriate management decisions.

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

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

2. CHARACTERISTICS AND REQUIREMENTS OF VARIOUS WATER USES

The complexity of the reservoir operation problem depends upon the extent to which the various intended purposes are compatible. If the purposes are relatively more compatible, comparatively less effort is needed for coordination. The various purposes for which a reservoir is used and the functional requirements for these purposes are as under:

a) Irrigation

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 and only a small fraction of the water supplied is available to the system as return flow. These requirements have direct correlation with the rainfall in the command area. In general, the demands will be minimum during the monsoon 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 the 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.

b) Hydroelectric power

The hydroelectric power demands usually vary seasonally and to a lesser extent daily and hourly too. The degree of fluctuation depends upon the type of loads being served, viz., industrial, municipal and agricultural. For example, in case of municipal areas, the hydroelectric demands are maximum during the peak summer months. Further, during the course of a day, two demand peaks are observed, one in the morning and another in the evening. Hydroelectric power demand comes under non-consumptive use of water because after passage through turbines, water can again be utilized for consumptive uses downstream. The amount of power generated depends upon the volume of water and the effective head.

c) Municipal and industrial water supply

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

d) Flood control

Flood control reservoirs are designed to moderate the flood flows that enter the reservoirs. The flood moderation is achieved by storing a fraction of inflows in the reservoir and releasing the balance water. The degree of moderation or flood attenuation depends upon the empty storage space available in the reservoir when the flood impinges it. 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.

e) Navigation

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

f) Recreation

The benefits from this aspect of reservoir are derived when the reservoir is used for swimming, boating, fishing and other water sports and picnic. Usually the recreation benefits are incidental to other uses of the reservoir and rarely a reservoir is operated for recreation purposes. The recreation activities are best supported when the reservoir remains nearly full during the recreation season. Large and rapid fluctuations in reservoir level are harmful to recreational points of view as they can create marshy lands near the rim of reservoir.

3. CONFLICTS IN RESERVOIR OPERATION

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

a) Conflicts in space

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

b) Conflicts in time

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

c) Conflicts in discharge

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

4. TECHNIQUES OF RESERVOIR OPERATION

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 regarding releases in different time periods in accordance with the demands.

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

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

4.1 Standard Linear Operating Policy

The simplest of the reservoir operation policies is the standard linear operating policy (SLOP). According to this policy, if in a particular period, the amount of water available in storage is less than the target demand, whatever quantity is available is released. If the water available is more than the target but less than target demand plus available storage capaicty, then a release equal to the target demand is made and the excess water is stored in the reservoir. In case, even after making releases equal to the target demands, there is no space to store the excess water, all the water in excess of maximum storage capacity is released. The SLOP is graphically represented in Figure-1.

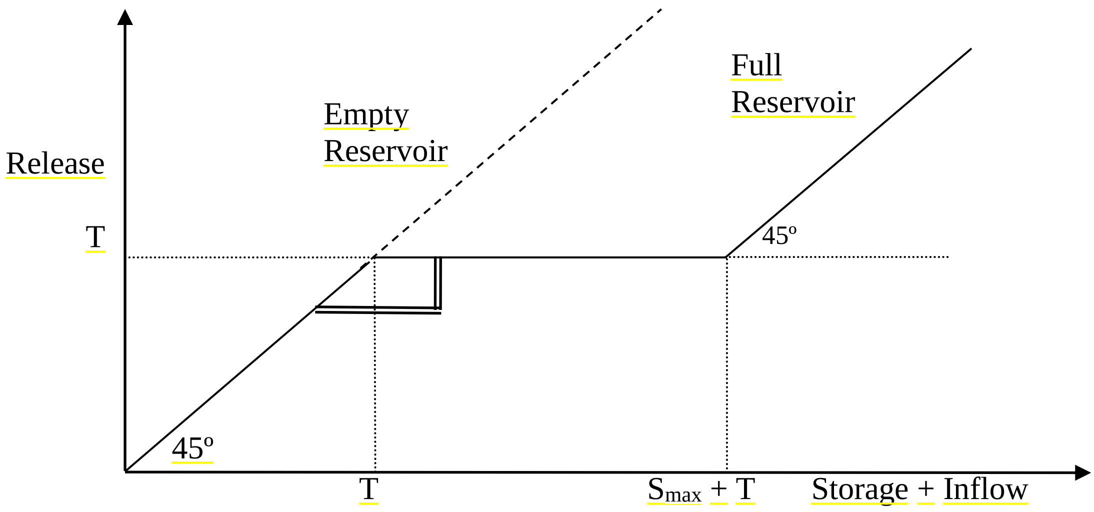

Figure-1 Graphical Representation of Standard Linear Operation Policy

The SLOP is a one-time operation policy without relation to the release of water at any other time. This type of time isolated releases of water is neither beneficial nor desirable. The water beyond the target output in any period has no economic value. This policy is not used in day-to-day operation due to its rigidness and above drawbacks. It is however, extensively used in planning studies.

4.2 Concept of Storage Zoning

In this concept, the entire reservoir storage space is conceptually divided in a number of zones by drawing imaginary horizontal planes at various elevations. The sizes of these zones need not remain constant and can vary with time. During the actual operation, the reservoir operators are expected to maintain the reservoir content in the specified zones. This conceptual division of reservoirs into a number of zones and the rules governing the maintenance of storage levels in a specified range are based upon the conviction that at a specified time, an ideal storage zone exists for a reservoir which, when maintained, gives the maximum expected benefits. This concept is in some way akin to concept of rule curve. The only added advantage here is that this approach gives more freedom or flexibility to the decision maker and he can manipulate the storage level within the specified zone. The rule governing the maintenance of reservoir level in a particular zone may be conditional upon the hydrologic state of the system. Thus, the reservoir operator may be asked to keep the level in one zone if streamflow is X and in another zone if the flow is Y.

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

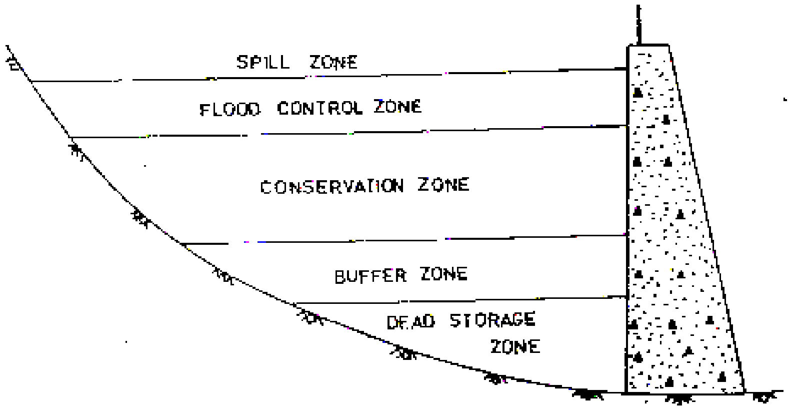

Figure-2 Reservoir zones for various purposes

4.3 Rule Curves

One type of management frequently used for reservoir operation is based on rule curves. A rule curve or rule level specifies the 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 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. 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 levels 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.

The rule curves implicitly reflect the established trade-off among various project objectives in the long run. For short-term operations they serve only as a guide. The operation of a reservoir by strictly following rule curves becomes quite rigid. Many times, in order to provide flexibility in operation, different rule curves are followed in different circumstances.

4.4 System Engineering Techniques

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

a) Simulation

Simulation is the process of designing a model of a system and conducting experiments with it for understanding the behaviour of the system and for evaluating various strategies for its operation. The essence of simulation is to reproduce the behaviour of the system. It allows for controlled experimentation without causing any disturbance to the real system. However, simulation analysis does not yield an immediate optimal answer and require a number of iterations to arrive at near-optimum solution.

Simulation models may be physical (a scale model such as a spillway operated in a hydraulics laboratory), analog (a system of electrical components, resistors and capacitors, arranged to act as analog of pipe resistances and storage elements), or mathematical (a compilation of equations that represent the actions of a system's elements). The vehicle used to operate mathematical models is normally the computer. In the area of water resources management, computerized models are becoming very popular nowadays. 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 the water resources systems is a time consuming and costly affair and the testing of different operating policies is not possible through 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, mathematical models are the most convenient to use.

The principal reason for carrying out simulation analysis is to learn as much as possible about how the existing or proposed system will react to conditions that might be expected to occur in the future. If a simulation model can be developed to represent a prototype system, then it can provide, in seconds or less, answers about how the real system would perform over years under different conditions of supply and demand. Thus, costly proposed projects can be evaluated to judge whether their performance would be adequate before investments are made. Similarly, operating policies can be tested before they are implemented in actual control situations. Where proposed designs and/or operating procedures do not meet the test, usually it is a straight-forward matter to revise the model to reflect changed policies and/or structural configuration.

b) Optimization

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

In Linear Programming, the objective function and constraints are linear function of decision variables. Optimum solution can be reached graphically or algebraically using simplex method. It also provides economic interpretation of the problem and carries out sensitivity analysis. The Dynamic programming is an optimization technique based on multistage decision process in which the decisions are taken in stages. It is an enumerating technique based on the Bellman's principle of optimality. It can be applied to both linear as well as nonlinear objective functions and constraints.

5. SIMULATION OF RESERVOIR OPERATION USING RULE CURVES

The water resources literature contains many discussions as to which systems approach, optimization or simulation, is better for operation analysis. There is a consensus now that the optimization models are more suited for screening studies while simulation models provide higher flexibility in detailed and realistic representation of complex systems. Repeated runs of a simulation model are made to analyze the system performance under different conditions. The advantage of a simulation model lies in its relatively accurate description of the simulated reality. Simulation is reproducible and therefore easy to check. The concepts inherent in simulation approach are easier to understand and communicate than other modeling concepts (Simonovic, 1992).

The simulation models associated with reservoir operation are usually based on the mass-balance and tracking the movement of water through a reservoir-stream system. These models are often used with historical streamflow records. Some widely used reservoir simulation models include HEC-3 and HEC-5 models developed by the Hydrologic Engineering Center of U.S. Army Corps of Engineers. The Texas Water Development Board has developed a series of surface water simulation models, for example, the SIMYLD-II model, TWDB (1972). Other popular models include the ACRES model (Sigvaldason 1976), the RESER model (Simonovic 1992), and the IRIS model (IRIS 1990).

5.1 Derivation of Rule Curves for Different Purposes

Each reservoir is operated according to the prevailing reservoir level and the elevation of different rule curve levels during the particular month. For a reservoir with hydropower, irrigation and water supply demands, four rule curves can be specified, a separate rule curve for each demand and one Upper Rule Curve (URC) beyond which water can be spilled from the dam. URC represents such water levels in the reservoir in different months such that if these are maintained throughout the year, all the demands from the reservoir can be met in full. Though it is always desirable to fill a reservoir up to FRL, it is generally recommended that some spill should be made from the reservoir to keep up the downstream river channel and to avoid encroachment in the river. Keeping the upper rule level below FRL (in monsoon months) can give extra room for flood absorption in the reservoir also. However, care should be taken that the conservation performance of the reservoir is not affected.

Position of rule curves for various demands depends on their relative priority. Starting upwards from the dead storage level, first lies the rule curve for the highest priority demand (water supply). This rule curve [also called Lower Rule Curve (LRC)] is calculated for the case when there is very high scarcity of water and it is not possible to meet any of the demands except for the full highest priority demand throughout the year. Below this rule curve, only the highest priority demands are met. Next lies the rule curve for second highest priority demand (irrigation/hydropower). This rule curve [also called Lower Middle Rule Curve (LMRC)] is calculated for the case when there is scarcity of water and it is not possible to meet all the demands except for the two highest priority demands throughout the year. If reservoir level in any month falls below this curve, then partial demands of the second highest priority demand and full demands of the highest priority demand are met. Above the lower middle rule curve lies the Upper Middle Rule Curve (UMRC) which represents the rule curve for least priority demand. This rule curve is calculated for the case when there is no scarcity of water and it is just possible to meet all the demands in full throughout the year. If the reservoir level falls in-between the UMRC and LMRC, then partial demands of the least priority demands and other demands in full are met. Four rule curves for a reservoir are illustrated in Figure-3. In all these rule curves, it is inherently assumed that the reservoir reaches the dead storage level at the end of water year.

For deriving rule curves for various purposes, monthly or any other time step inflow series at the site of reservoir is analyzed and inflow values corresponding to different probability levels like 50%, 60%, 75%, 80% and 90% are worked out for that time step using statistical approach. Using this dependable inflow series, the water availability is assumed as corresponding to particular probability of inflow series. Then, for deriving critical rule levels for different purposes say water supply, irrigation, hydropower generation etc., the water availability is assumed for a particular probability and the reservoir is assumed to be empty at the end of the water year. Then, computations of end-of-month reservoir levels are made after allowing for water demands and evaporation losses from the reservoir surface. Rule curves for different demands are computed separately. First, computations are made for the highest priority demands and then for subsequent lower priority demands as explained below:

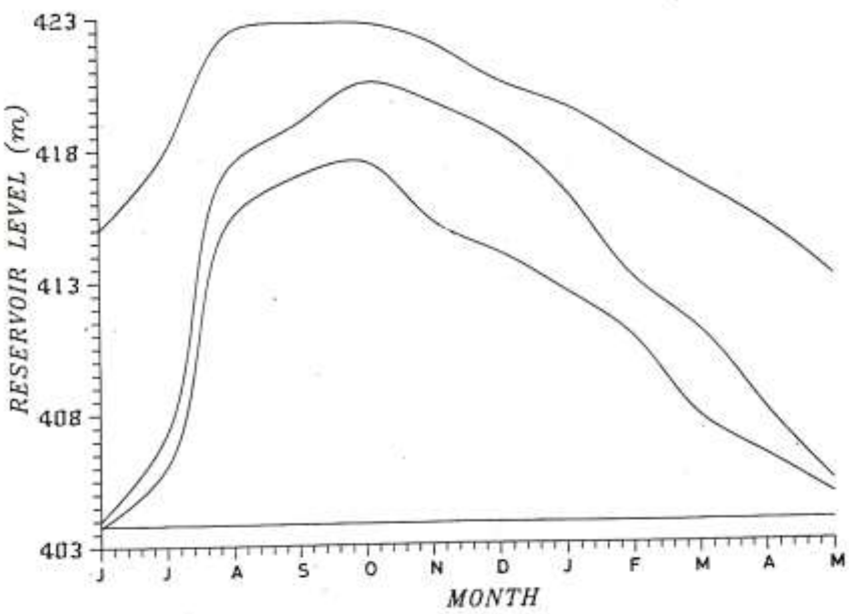

Figure-3 Reservoir Rule Curves for Different Purposes

a) Rule level computation for highest priority conservation demands

The rule curves for various demands are calculated for the case when there is scarcity of water in the reservoir and it is just possible to meet various demands in full throughout the year. Rule levels for highest priority demands like water supply for domestic and industrial purposes, minimum flow requirements etc. are calculated assuming the following conditions:

i) Reservoir level reaches to dead storage level by the end of water year (May end).

ii) 90% reliable inflow (very low amount of inflow) is entering the reservoir.

iii) Only highest priority demands are being satisfied.

Backward computations are made starting from the end of May. Evaporation loss is considered at normal monthly rate over the surface area of the reservoir corresponding to a particular elevation. The following formula is used:

$$Storage_{begin} = Storage_{end} - Inflow + Demand + Evaporation + Spill \quad ...(1)$$

Thus effort is made to find such a level at which all the highest priority demands can be satisfied in full even if very low flow enters the reservoir.

b) Rule level computation for other conservation demands

Rule levels for other conservation demands like irrigation, hydroelectric power etc. is calculated assuming the following conditions:

i) Reservoir level reaches to dead storage level by the end of water year (May end).

ii) 75% reliable inflow is entering the reservoir.

iii) The demand under consideration and other higher priority demands are met in full.

Backward computations are made starting from the end of May and evaporation loss is considered at normal monthly rate over the surface area of the reservoir corresponding to a particular elevation. The formula given in equation (1) is used. Thus effort is made to find such a level that if the reservoir level is above this level, then demand under consideration and higher priority demands can be satisfied in full and there is no need to curtail the demands. If the inflow to the reservoir is so less that this level can not be maintained, then supply for meeting demands need to be curtailed.

c) Uppermost rule level computation

All the rule curves calculated above are derived for scarcity situations so as to foresee the critical conditions in the reservoir and to timely regulate the supply of water for various purposes. The uppermost rule levels are calculated for the case when there is sufficient inflow in the reservoir and it is possible to spill some water without affecting its performance. Though it is most desirable to fill the reservoir up to FRL, sometimes, it is required to spill water from the reservoir to keep up the downstream channel and to avoid encroachment in the river bed. The conditions which are presumed for deriving upper rule curve are:

i) Reservoir level is at FRL after the end of monsoon period (September end).

ii) 50% reliable inflow is entering the reservoir.

iii) All conservation demands from the reservoir are being met in full.

Forward calculations are carried out starting from the FRL up to end of May in the next year. Evaporation loss is considered at normal monthly rate over the surface area of the reservoir corresponding to a particular elevation. The following formula is used:

$$Storage_{end} = Storage_{begin} + Inflow - Demand - Evaporation - Spill \quad ...(2)$$

The rule curve in four monsoon months is kept at FRL and these levels are subsequently lowered using simulation studies. Effort is made to find such level that our demands can be satisfied in full.

5.2 Operation of a Reservoir Using Rule Curves

After the derivation of initial rule curves for different purposes, the operation analysis is carried out for the reservoir and the rule curves are fine-tuned till the performance of the system could be improved. Finally derived rule curves are the operation rule curves which will be used to guide the operation of reservoir in actual field conditions.

At any time, the reservoir is operated according to the prevalent water level and the elevation of different rule curve levels for the corresponding time. Let us assume that a reservoir is meant to serve for water supply (highest priority), irrigation (next priority), and hydropower (least priority). For these purposes, three operating rule curves are prepared, say curve 'W' for water supply, Curve 'I' for irrigation, and curve 'H' for hydropower. In addition to these, one upper rule curve, say curve 'U' is prepared. The procedure for rule curve based operation is given in following steps:

- At any time step, if the present water level in the reservoir exceeds level 'U', then spill is made from the reservoir and the water level is brought to Level 'U'.
- If the present reservoir level falls below level 'U' but exceeds level 'H', full supply is made for meeting all demands from the reservoir but no spill is made.
- If the present reservoir level falls below level 'H' but exceeds level 'I', then supply for the hydropower generation is curtailed (say, by 25%) while full demands of irrigation and water supply are made from the reservoir.
- If the present reservoir level falls below level 'I' but exceeds level 'W', then supply for the irrigation is curtailed (say, by 25%) while minimum demands for hydropower (if any) and full water supply demands are made from the reservoir.
- If the present reservoir level falls below level 'W', then release (full or partial) is made only for water supply demands and no release is made for irrigation or hydropower demands.

The underlying assumption in such an operation procedure is that it would always be better to supply less water throughout the year rather than meeting full demands for some time and then stopping the supply suddenly. The operation of a reservoir by strictly following the rule curves becomes quite rigid. 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. A flexible reservoir operation schedule can be maintained for those reservoirs which have adequate streamflow forecasting system. Further, in order to provide flexibility in operation, different rule curves can be developed to represent various scenarios.

5.3 Possible Refinements in Rule Curve Based Operation

We should be aware of the drawbacks of rule curve based operation so that refinements can be made in the rule curves while actually operating the reservoir. First of all we may question "Is the passed streamflow record the best criterion for future dependable flow operation?" To counter for this drawback, it becomes necessary to conduct probability studies of flow periods, and to carry out simulation study before the final rule curve can be recommended.

Another refinement may have to be made in connection with changing demand patterns. In the derivation of the rule curve, the mass curve of demand is based on one particular set of demands in a water year; and the resultant rule curve is only valid for those set of demands. However, for actual reservoir operation we must allow for the growing demands. Hence the mass curve of demand must reflect the change in demand pattern from year to year.

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