INTRODUCTION TO RESERVOIR SYSTEMS

by

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THE NEED FOR RESERVOIRS

Among the various components of a water resources development project, reservoirs are the most important. A reservoir is created by constructing dam across a stream. 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.

THE RESERVOIR SYSTEM

The terms which are used in connection with a reservoir system are described here.

The amount of storage available in a reservoir can be conceptually divided in several zones. Most commonly the division is among following five sub-zones:

(i) Dead Storage Zone

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

(ii) Buffer Zone

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

(iii) Conservation Zone

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

(iv) Flood Control Zone

This is the storage space exclusively earmarked for absorbing floods during high flow periods. This zone is located on top of conservation zone. The releases are increased as necessary when the water stored in the reservoir falls in this zone.

(v) Spill Zone

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

The entire reservoir storage which lies above the inactive storage is called live or active storage. All the storage zones described above are shown in Fig. 1.

(vi) Within-year Storage

This term is used to denote the storage of a reservoir which is constructed to provide water for a small period say of the order of few months. This type of reservoir may spill and run dry several times in a year.

(vii) Carryover Storage

In many cases, the entire water stored in a reservoir is not used up in a year and some water is carried over to the next year. This amount is called carryover storage.

(viii) Conceptual Storages

Three terms related to conceptual storage are particularly useful in computation of reservoir capacity. As defined by McMahon and Mein (1978), a finite storage is the storage which can spill as well as run dry. A semi finite storage is the storage of a reservoir which has no lower bound, i.e., it is a bottomless reservoir which can spill but never run dry. It is contrasted from an infinite storage which has no upper bound - a topless reservoir which can become empty but never spills.

(ix) Normal Conservation Level (NCL)

This is the highest level of reservoir at which water is intended to be held for various uses, other than the flood control. Generally it refers to the top of conservation zone.

(x) Full Reservoir Level (FRL)

This is the highest level of the reservoir up to which the water stored for conservation various uses, including part or total of flood storage without allowing any passage of water through the spillway.

(xi) Maximum Water Level (MWL)

It is the highest level to which the reservoir water will rise while passing the design flood with the spillway facilities in full operation. This level refers to the top of spill zone.

(xii) Minimum Drawdown Level (MDDL)

This level corresponds to the reservoir level below which no withdrawal is permissible except by evaporation or seepage losses.

(xiii) Maximum probable flood (MPF)

It is the flood which may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region and is computed by using the maximum probable storm which is an estimate of the physical upper limit to the storm rainfall over the basin.

(xiv) Standard Project Flood (SPF)

It is the flood that may be expected from the most severe combination of meteorologic and hydrologic conditions considered reasonably characteristic of the region. It is computed from the standard project storm rainfall which is reasonably capable of occurring over the basin in question and may be taken as the largest storm which has occurred in the region of the basin during the period of weather record.

(xv) Design Flood

This is the flood adopted for spillway design purposes. It may be the maximum probable flood, standard project flood, or a flood corresponding to some desired frequency of occurrence depending upon the standard of security that should be provided against failure.

(xvi) Release

Release or draft is the amount of controlled outflow from a reservoir during a given time interval to satisfy the various demands.

(xvii) Yield

For the reservoirs serving for irrigation, or water supply, or municipal or industrial areas, the amount of water released for these purpose is called the reservoir yield. For the reservoirs where the stored water is used to generate hydroelectric power, yield is defined as the amount of power generated during a time interval.

(xviii) Firm Yield

Firm water yield from a reservoir is defined as the maximum quantity of water that can be guaranteed to be delivered 100% of time each year according to some prescribed monthly distribution. Firm power yield of a reservoir can also be described in a similar manner.

(xix) Reliability

Reliability of a system is described by the probability X that the system is in the satisfactory state. Hence

$$\alpha = \text{Prob}\ [x_t \epsilon\ S]$$

Where x_t is the state of the system at the time t and S is the domain of admissible states. Further, risk, which is the probability of failure is $(1-\alpha)$.

(xx) Annual Reliability

Defining a failure as occurrence of an outflow less than demand, annual reliability is the probability that no failure will occur within a year. Mathematically

$$R_a = (n-m)/n$$

Where m is the number of failure years in total n years.

(xxi) Time Reliability

Time reliability is the portion of the total operation time during which the demand was fully satisfied.

$$R_t = \sum_{y \geq q} \Delta t \ / \ T$$

Where T is the period of operation, q is the target and y is the release.

(xxii) Volume Reliability

This is the actually delivered portion of the total volume of demand during the period T. Hence

$$R_v = 1 - \int_{y<q} (q-y)\ dt \ / \ \int_0^T q\ dt$$

In case of constant target demand, the relation among annual reliability, time reliability and volume reliability is

$$R_a \leq R_t \leq R_v$$

The reason of this behavior of these indices is that most failure years contain periods of nonfailure operation and that during most failure periods the release is not completely curtailed.

(xxiii) Resiliency

Resiliency describes how quickly the system recovers from failure once the failure has taken place. Resiliency is described as the inverse of expected value of the length of time a system's output remains unsatisfactory after failure.

(xxiv) Vulnerability

Vulnerability refers to the likely magnitude of a failure if it occurs. Here emphasis is placed on how severe the failure is but not on how long it persists.

CHARACTERISTICS AND REQUIREMENTS OF WATER USES

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 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 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.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 hydroelectric power generated at a plant depends upon the volume of water passed through turbines 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 by a reservoir which remained nearly full during the recreation season. Large and rapid fluctuations in water level of a reservoir are harmful to recreational points of view as they can create marshy lands near the rim of reservoir.

CLASSIFICATION OF RESERVOIRS

Depending upon the number of purposes which a reservoir is to serve, a reservoir may be classified as a) Single purpose reservoir, or b) Multipurpose reservoir.

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

Depending upon the storage provided, a reservoir may be classified as a) Seasonal storage reservoir or b) Over-year storage reservoir.

Seasonal storage reservoirs are designed to serve conservation purposes for a limited period of low flows. These reservoirs fill up and spill frequently. These reservoirs are normally constructed on small tributaries and serve relatively smaller area. The reservoir may also give certain incidental flood control benefit.

Over-year storage reservoirs water availability in 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.

RESERVOIR OPERATION PROBLEM

Once the structured facilities like dams, barrages, hydropower plants, which are required for utilization of water resources come into being, the benefits that could be reaped depend to a large extent upon how these facilities are managed. Thus the efficient use of water resources requires not only judicious design but also proper management after construction. Reservoir operation forms a very important part of planning and management of water resources system. Once a reservoir has been developed, detailed guidelines 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. A single purpose reservoir is constructed to serve only one purpose. The operation problem for such reservoir is to decide about the releases to be made from the reservoir so that the benefits for that purpose are maximized. For a multipurpose reservoir, in addition to the above, it is also required to optimally allocate the release among several purposes.

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.

CONFLICTS IN RESERVOIR OPERATION

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

(a) Conflicts in Space

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

(b) Conflicts in Time

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

(c) Conflicts in discharge

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

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 releases in different time periods in accordance with the demands.

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

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

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 2.

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.

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.

Concept of Storage Zoning

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

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 the future requirements up to the end of the operating horizons. When the amount of water is anticipated to be short compared to the demand, releases may be curtailed. The limits of various zones may vary with time.

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 the optimum solution.

(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.

REFERENCES

Hall, W.A., and J.A. Dracup, Water Resources Systems Engineering, Tata McGraw-Hill Publishing Company, New Delhi, 1979.

McMahon, T.A., and R.G. Mein, Reservoir Capacity and Yield, Elsevier Book Company, Sydney.

Loucks, D.P., J.R. Stedinger, and D.A. Haith, Water Resources Systems Planning and Analysis, Prentice Hall Inc., New Jersey, 1981.

Rao, S.S., Optimization, Theory and Practice, Wiley Eastern, 1979.

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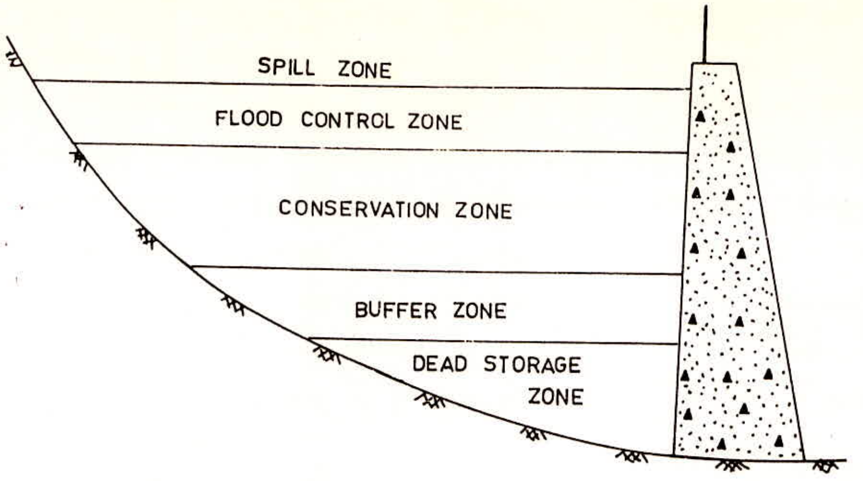

Fig. 1 Conceptual Representation of Reservoir Zones

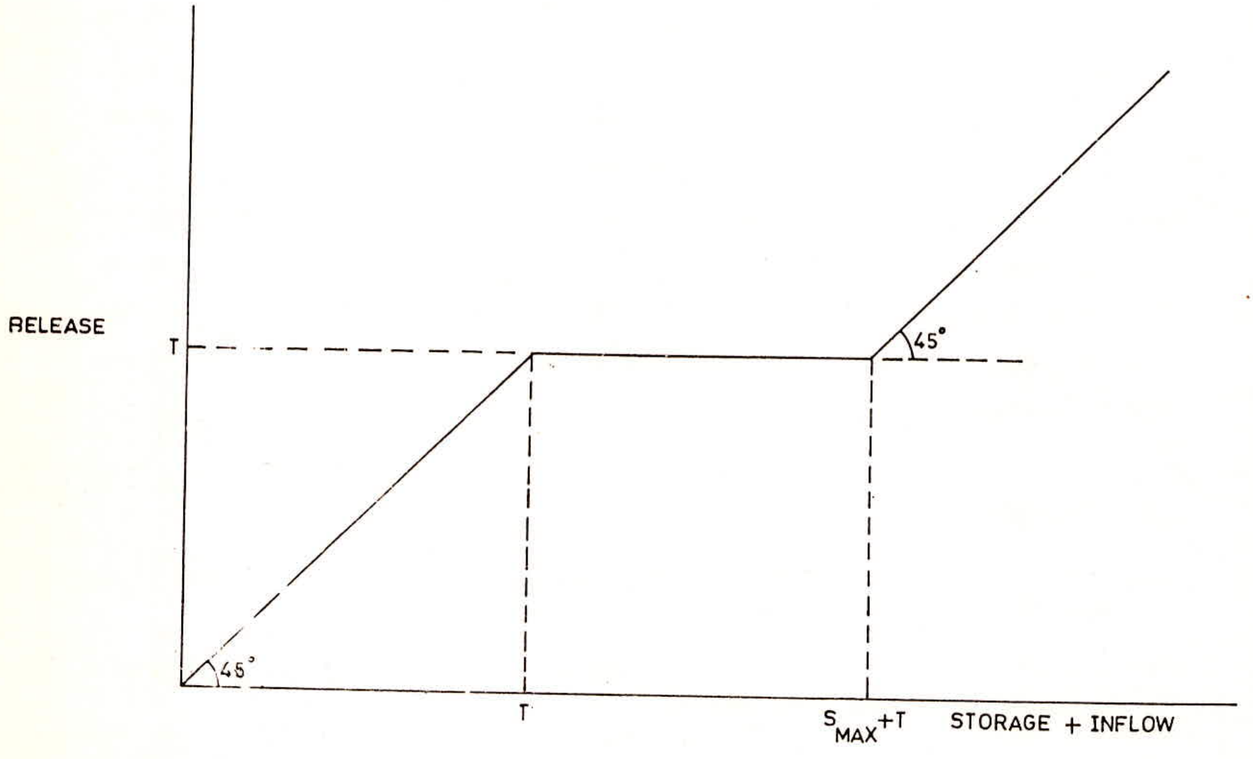

Fig. 2 Graphical Representation of Standard Linear Operation Policy

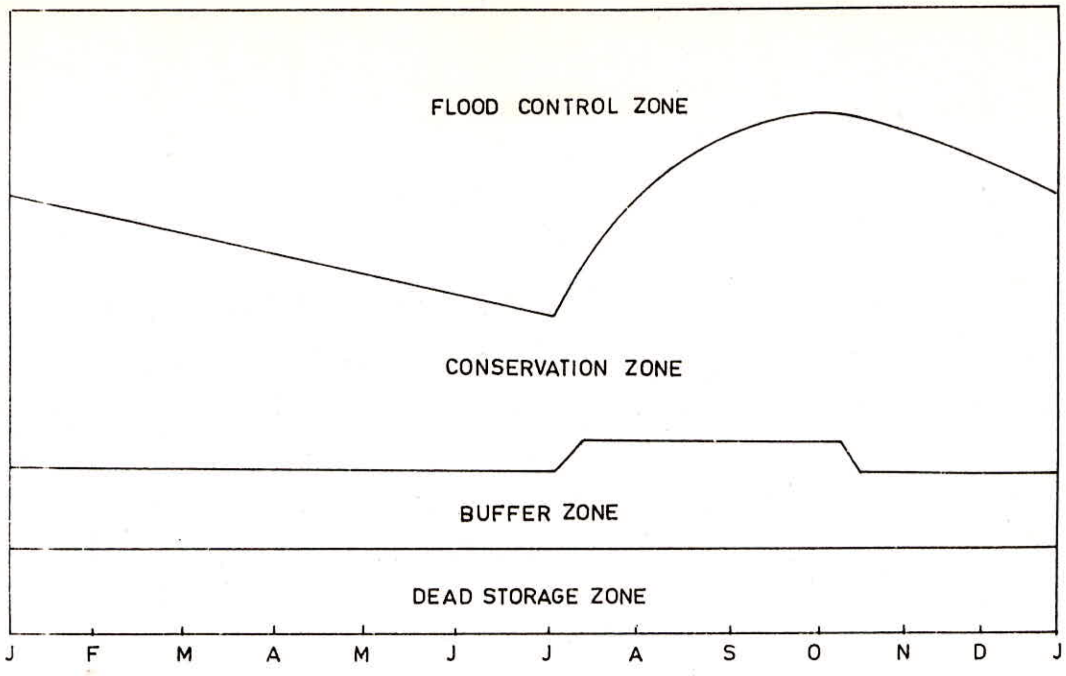

Fig. 3 Variation of Reservoir Zones with Time