TRAINING COURSE

ON

RESERVOIR OPERATION

(UNDER WORLD BANK AIDED HYDROLOGY PROJECT)

Module 1

Introduction

To

Reservoir Systems

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INTRODUCTION TO RESERVOIR SYSTEMS

1.1 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.

1.2 THE RESERVOIR TERMINOLOGY

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

a) 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.

b) 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.

c) 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.

d) 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.

e) 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.

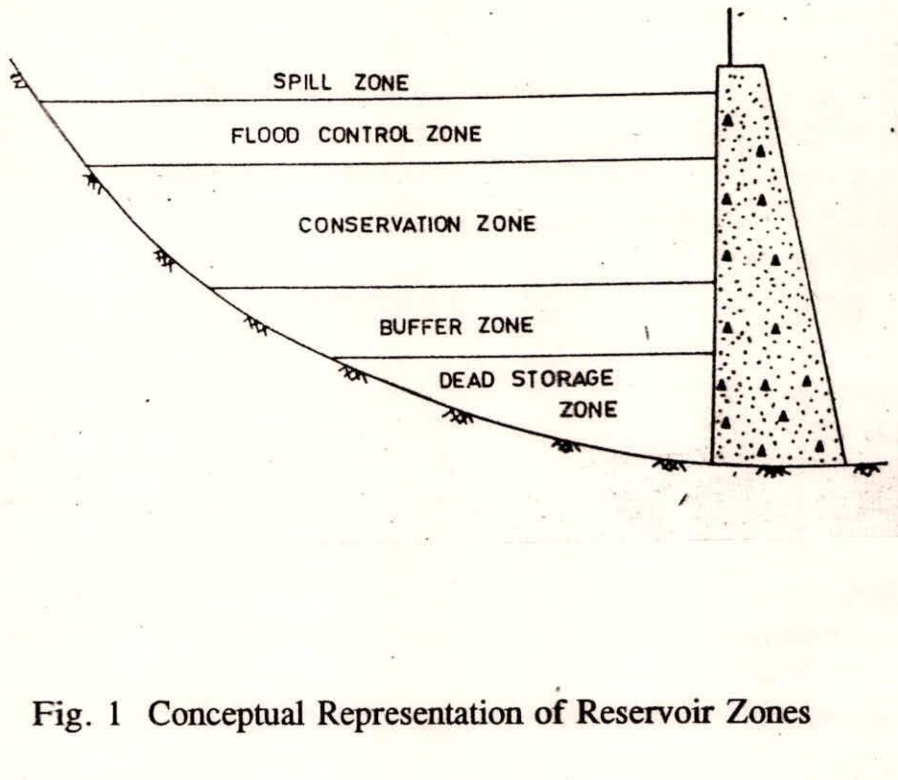

Fig. 1 Conceptual Representation of Reservoir Zones

f) 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.

g) 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.

The term *bank storage* is used to denote the storage absorbed and stored in the bed and banks of a stream, in the voids in the soil cover in a reservoir and becomes available in whole or in part as seepage water when the water level drops down.

h) 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.

i) Full Reservoir Level (FRL)

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

j) 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.

k) Minimum Drawdown Level (MDDL)

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

l) 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.

m) 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 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.

n) 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.

o) Release

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

p) Yield

For the reservoirs serving for irrigation, or water supply for 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.

q) 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 is the minimum continuous power that can be generated 100% of time. The additional power, over and above the firm power, is termed as *secondary power*.

The elevation-storage and elevation-area curves and various operting levels for a typical hydropower reservoir are shown in Fig.-1a below.

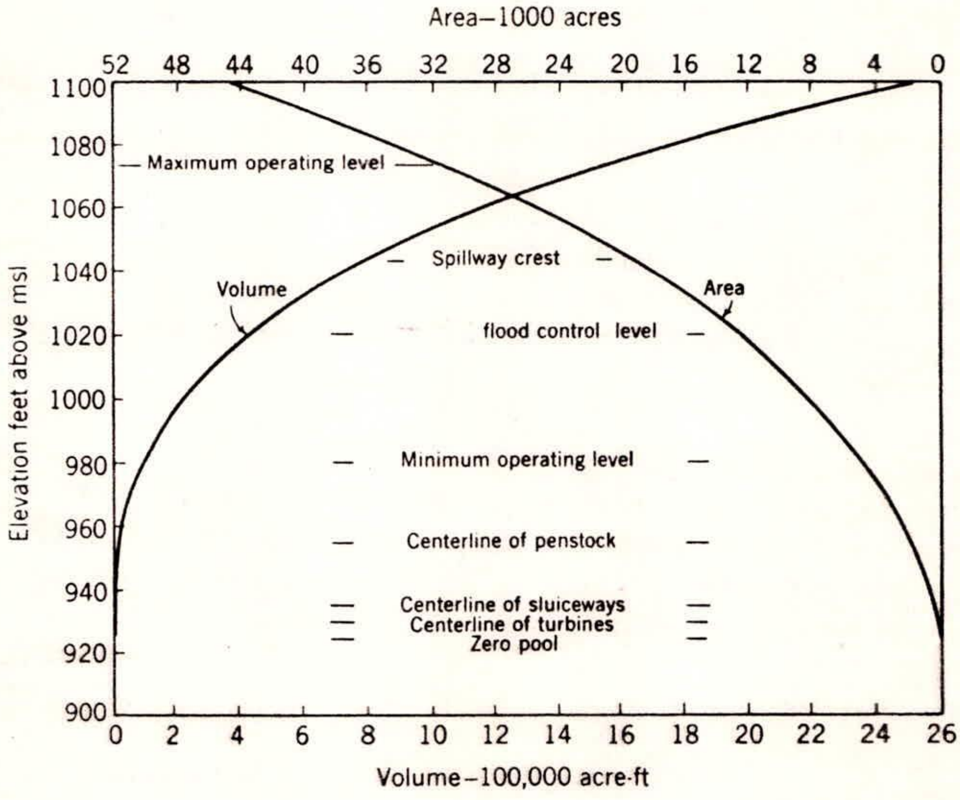

Fig.-1a Elevation-Area-Storage and Various Operting Levels for a Hydropower Reservoir

r) Reliability

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

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

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 $(1-\alpha)$. The reliability of a reservoir is defined as the probability that it will deliver the expected demand throughout its lifetime without incurring a deficiency. In this sense lifetime is taken as the economic life, which is usually between 50 and 100 years. The reliability analysis permits one to compare the costs of achieving various levels of reliability and to determine whether an increase in reliability is warranted.

s) 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.

t) 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.

u) 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 non-failure operation and that during most failure periods the release is not completely curtailed.

v) 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.

w) 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.

1.3 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 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 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.

1.4 CLASSIFICATION OF RESERVOIRS

There are many ways in which the reservoirs can be classified. These are described below.

a) Depending Upon Number of Purposes

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. A reservoir which is designed for one of the purposes but provides other incidental benefits, because every reservoir serves or should serve more than one purpose on account of indirect benefits that may result from its operation, is also referred to as multipurpose reservoir. Keeping with the diverse purposes served by a multipurpose reservoir, it is usually of large capacity so as to (i) reserve a certain minimum empty storage capacity at all times for flood control, (ii) provide steady supply for kharif and rabi crops, (iii) generate maximum firm power. Usually the enormous benefits accruing from a multipurpose project repay the cost of building the dam within a couple of years.

b) Depending Upon Storage

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.

In the *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.

c) Based On The Purpose Served

A *Storage reservoir*, also termed as *conservation reservoir*, stores surplus water during the period of excess flow for a considerable length of time so as to maintain continuous supply for irrigation, hydel power generation, municipal water supply and industrial purposes during the periods of lean flow in the river but when demand is high.

A *Distribution reservoir* is a reservoir connected with water supply project of a city or a town. It is usually of limited storage capacity and is used primarily to cater for fluctuations in demand which may occur over short periods of several hours to several days and also as local storage to take care of emergency in the event of break in main supply line or failure of the pumping plant, etc. The water is stored during the period of no demand or slack demand to meet the demand in excess of constant pumping rate from the storage during the period of maximum demand. The reservoir thus permits the pumping plants and water treatment plants to work at uniform rate.

A *Balancing reservoir* is a reservoir, usually of limited capacity, located downstream of (or subsidiary to) a main reservoir to (a) store the water let down from the reservoir in excess of that required for irrigation or additional power generation, (b) provide flexibility of operation to the distribution system, and (c) at certain locations primarily for permitting regulated supply to the power penstocks with a view to cater for the fluctuations in requirement of water supply to the turbines.

An *Auxiliary reservoir*, also termed as *compensatory reservoir*, supplements and absorbs the spill of a main reservoir.

A *Flood control reservoir* holds back a part volume (in excess of the safe carrying capacity of the river channel downstream) temporarily during floods and releases it later, when flood recedes, as rapidly as the channel capacity permits. Flood control reservoir thus reduces flood stage and consequently avoids damage downstream. Construction of reservoir solely for flood control measures is not advisable except in very special cases due to the high cost of construction. Flood control reservoirs may be either retarding reservoirs or detention reservoirs.

Retarding reservoirs are those at which gates are provided in the outlets to regulate the releases but the discharging capacity of the outlets and spillway is so fixed that it is not in excess of the flood carrying capacity of the downstream channel. With the rise in reservoir level, the amount of water released is such as would not create flooding the areas downstream. They are preferred on small rivers. The suitable location of a retarding reservoir is immediately upstream of the city to be protected from floods or above the confluence or two or more streams.

Detention reservoirs are those which have gated outlets and store water for a relatively brief period of time so as to provide greater flexibility in the operation of reservoirs. They are specially suitable when the area under control increases in size and protected area is widespread.

1.5 PHYSICAL CHARACTERISTICS OF RESERVOIRS

Since the primary function of reservoirs is to provide storage, their most important characteristic is storage capacity. Capacity of reservoirs on natural sites must usually be determined from topographic surveys. An area-elevation curve is constructed by planimetering the area enclosed within the reservoir site. The integral of the area-elevation curve is the elevation-storage or capacity curve for the reservoir.

Normal pool level is the maximum elevation to which the reservoir surface will rise during ordinary operating conditions. For most reservoirs, the normal pool is determined by the elevation of the spillway crest or the top of the spillway gates. Minimum pool level is the lowest elevation to which the pool is to be drawn under normal conditions. This level may be fixed by the elevation of the lowest outlet in the dam or, in the case of hydroelectric reservoirs, based on operating efficiency considerations for the turbines.

1.5.1 Reservoir Yield

Probably the most important aspect of storage reservoir design is an analysis of the relation between yield and capacity. Yield is the amount of water that can be supplied from the reservoir during a specified interval of time. The time interval may vary from a day for a small distribution reservoir to a year or more for a large storage reservoir. Yield is dependent on inflow and will vary from year to year. The safe, or firm yield is the maximum quantity of water that can be guaranteed during a critical dry period. In practice, the critical period is often taken as the period of lowest natural flow on record for the stream. Hence, there is a finite probability that a drier period may occur, with a yield even less than the safe yield. Since firm yield can never be determined with certainty, it is better to treat yield in probabilistic terms. Water available in excess of safe yield during periods of high flow is called secondary yield. Hydroelectric enérgy developed from secondary water may be sold to large industries on a "when available" basis. Energy commitments to domestic users must be on a firm basis.

1.5.2 Reservoir Sedimentation

Every stream carries some suspended sediment and moves larger solids along the stream bed as bed load. Since the specific gravity of soil materials is about 2.65, the particles of suspended sediment tend to settle to the channel bottom, but upward current in the turbulent flow counteract the gravitational settling. When sediment-laden water reaches a reservoir, the velocity and turbulence are greatly reduced. The larger suspended particles and most of the bed load are deposited as a delta at the head of the reservoir. The smaller particles remain in suspension for a long time and some may pass the dam with water discharged through sluiceways, turbines or the spillway.

The ultimate destiny of all reservoirs is to be filled with sediment. If the sediment inflow is large compared with the reservoir capacity, the useful life of the reservoir may be very short. There are instances of reservoirs being filled-up within a few years of their operation; a small water-supply reservoir in the USA, was filled with sediment during the first year after its completion. Reservoir planning must include consideration of the probable rate of sedimentation in order to determine whether the useful life of the proposed reservoir will be sufficient to warrant its construction.

Our knowledge of reservoir sedimentation rates is based on surveys to determine the rate of sediment accumulation in reservoirs that have been in existence for many years. These surveys indicate the specific weight of the settled sediments and the percentage of entering sediment that is deposited in the reservoir. These data are necessary in order to interpret the data on sediment load of streams in terms of reservoir sedimentation. Sediment transport fluctuates widely from near zero during dry weather to extremely large quantities during major floods. Consequently, it is very difficult to predict the sediment accumulation to be expected during a short period of time. Conversely, it is unwise to assume that the accumulation during a period of a few years can indicate the true average annual sediment transport.

The percentage of the inflowing sediment that is retained in a reservoir (trap efficiency) is a function of the ratio of reservoir capacity to total inflow. A small reservoir on a large stream passes most of its inflow so quickly that the finer sediments do not settle but are discharged downstream. A larger reservoir, on the other hand, may retain water for several years and permit almost complete removal of suspended sediment. The trap efficiency of a reservoir decreases with age as the reservoir capacity is reduced by sediment accumulation. Thus complete filling of the reservoir may require a very long time, but actually the useful life of the reserves is terminated when the capacity occupied by sediment is sufficient to prevent the reservoir from serving its intended purpose.

1.5.3 Reservoir Sedimentation Control

The most common procedure for dealing with the sediment problem is to designate a portion of the reservoir capacity as sediment storage. This is a negative approach that in no way reduces the sediment accumulation but merely postpones the date when it becomes serious. Since sediment is deposited all through the reservoir, the allocation for sediment storage cannot be exclusively the dead storage but must also include some otherwise useful storage. Actually, reservoir sedimentation cannot be prevented, but it may be retarded. One way of doing this is to select a site where the sediment inflow is naturally low. Some basins are more prolific sources of sediment than others because of soil type, land slopes, vegetal cover, and rainfall characteristics. If an alternative site exists, prolific sediment sources should be avoided. After a site has been selected, the reservoir capacity should be made large enough to create a useful life sufficient to warrant the construction. Although trap efficiency of a large reservoir is high, it does not increase linearly, and the useful life of a large reservoir is longer than that of a small reservoir if all other factors remain constant.

1.5.4 Reservoir Clearance

The removal of trees and bush from a reservoir site is an expensive operation and is often difficult to justify on an economic basis. The main disadvantages resulting from leaving the vegetation in the reservoir are the possibilities that (1) trees will eventually float and create a debris problem at the dam, (2) decay of organic material may create undesirable odors or tastes in water-supply reservoirs, and (3) trees projecting above the water surface may create an undesirable appearance and restrict the use of the reservoir for recreation.

Frequently all timber that would project above the water surface at minimum level is removed. This overcomes most of the problems cited earlier at some savings over the cost of complete clearance.

1.5.5 Density Currents

Density current is defined as the gravity flow of fluid under, over or through another fluid of approximately equal density or the density of which differs by a small amount from that of the primary current. Further, it is essential that two fluids are miscible and that the density difference be a function of differences in temperature, salt content and/or sediment content of the two fluids, but independent of pressure intensity and elastic properties of the fluid. A sediment laden inflow with density greater than the reservoir water descends to the lower water layers and moves there in the direction of the dam. Such underflows are one of the common types of density currents.

Density currents of importance in reservoirs are those that transport sediments from upper and higher parts of the reservoir to its lower reaches especially to the dam. The inflowing muddy water may plunge directly, on entry in the reservoir, with the clear still water of the reservoir and partial mixing occurs due to the losses involved in the change of momentum caused by the reduction in velocity of flow. The rate of silting of reservoirs can be reduced if the density currents are vented through the outlets, and sluice gates properly located and operated in the body of the dam so that a major portion of the sediment laden water entering the reservoir can be ejected downstream of the dam in the form of density currents before it has a chance to settle down.

1.5.6 Trap Efficiency

Reservoir sedimentation is measured in terms of trap efficiency. Trap efficiency is defined as the ratio of sediment retained in the reservoir to the sediment brought by the water into the reservoir. The trap efficiency primarily depends on the sediment load characteristics, and the detention time of the inflow, method of reservoir operation and age of reservoir.

Trap efficiency is computed based on the inflow and outflow of sediment assessed from the sediment observations in the downstream immediately after the outlets. Some empirical relations based on the generalized trap efficiency actually observed are available. From these relations, the amount of sediment which a new reservoir will trap can be determined against the known values of the average annual sediment load of the stream. The volume or the weight is computed from the known specific weight of the sediment in actual conditions at the reservoir.

While allocating space for dead storage in most cases, the trap efficiency is considered at least 95% and only on rare and special occasions it falls below 90%. Observations at Bhakra and Beas reservoirs have revealed that the trap efficiency is almost 99%, and 97%, respectively.

1.6 RESERVOIR LOSSES

The loss of water from a reservoir is mainly due to evaporation and seepage.

1.6.1 Evaporation Losses

Evaporation losses from a reservoir depend on the water spread area of the reservoir and the rate of evaporation which varies directly with temperature of air and water and wind velocity and inversely with humidity. The evaporation losses are measured in cm of water depth. For the estimation of evaporation losses, it is essential to observe the evaporation loss at or near the reservoir site with pan evaporimeters.

For the Indian subcontinent, loss of water by evaporation generally varies from 150 to 200 cm depth of stored water annually; a maximum of 350 cm in parts of Rajasthan and Saurashtra and a minimum of 50 cm in parts of Jammu and Kashmir. Evaporation in hot months of May and June is two to five times than in winter months of December and January.

The monthly evaporation loss from a reservoir is calculated by multiplying the average water spread area in the reservoir during the month with the monthly evaporation loss depth as observed from the evaporimeter.

1.6.2 Seepage Losses

Seepage losses are difficult to estimate and are not important in most cases. Seepage losses are generally more when the reservoir is underlain by porous strata having ample outlets beneath the surrounding hills or under the dam. Absorption loss may be significant in the initial stages but gradually reduces as the soil pores become saturated. Generally the reservoir banks are not so permeable as to cause leakage of any significance. Where the banks have continuous seams of porous strata or made of fractured rock formation, pressure grouting is done to seal the fractured rock. The water lost from the reservoir to the ground water through seepage and passages in the reservoir bed is not amenable to measurement. However, an assessment of the losses can be made by considering the inflow, the outflow, and the precipitation over the reservoir and evaporation loss and then working out the unaccounted loss of water due to seepage and absorption. The accuracy of the determination evidently depends upon the precision with which other connected observations are made.

2.0 RESERVOIR OPERATION PROBLEM

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.

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.

2.1 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.

2.2 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 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.

2.2.1 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 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.

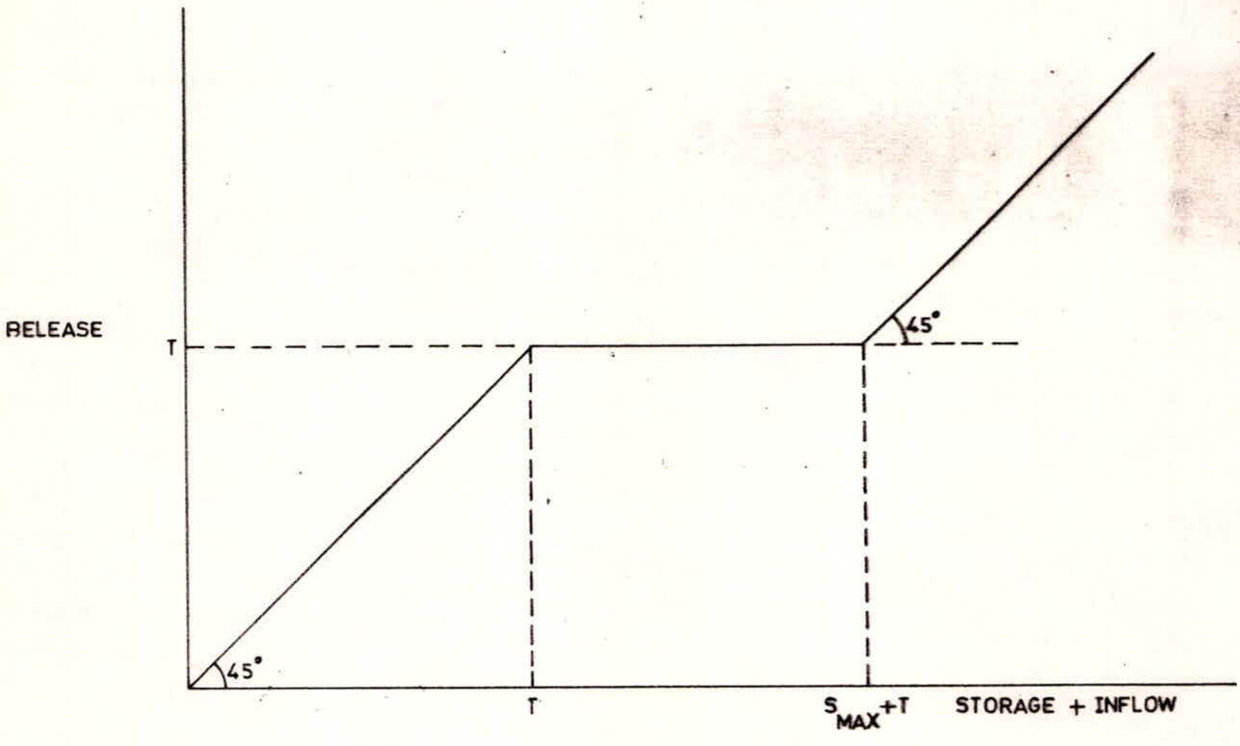

Fig. 2 Graphical Representation of Standard Linear Operation Policy

2.2.2 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 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, as shown in Fig. 3.

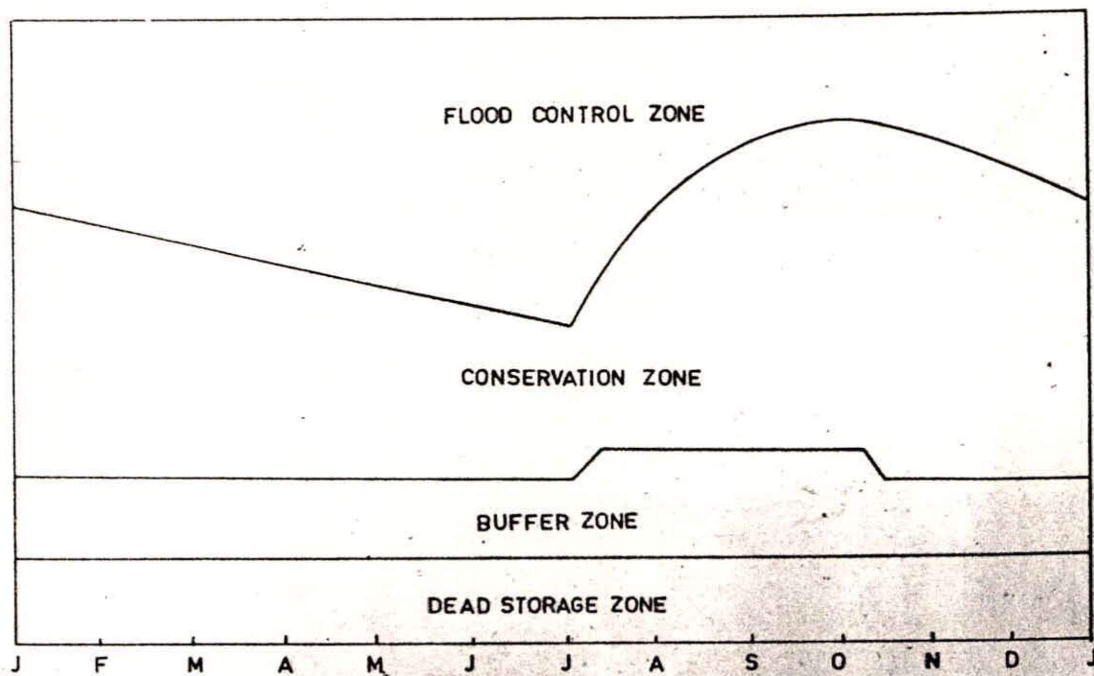

Fig. 3 Variation of Reservoir Zones With Time

2.3 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.

2.4 SYSTEM ENGINEERING FOR RESERVOIR MANAGEMENT

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.

2.4.1 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.

2.4.2 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.

2.5 ENVIRONMENTAL IMPACTS OF RESERVOIRS

The creation of reservoirs results in far-reaching changes in the ecosystem. The major effect is on the land which is inundated and on the aquatic environment. Sedimentation, soil erosion. stratification, adverse effect on fish and proliferation of aquatic weeds are some of the major disruptions in the ecosystem which may involve economic loss. The effect of reservoirs on the terrestrial environment are generally felt in case of forests, wild life, ground water, climate and agriculture. Human environment is affected in respect of alteration of human settlement and occupational patterns etc. and water borne diseases. An increasing constraining factor in hydropower development has been the conflict between the expanding electric energy demands and the concern for environmental effects of reservoirs. Compared to high head dams, low head hydropower projects are less destructive to aquatic life, and cause less damage to the general environment and other aesthetic factors. However, an understanding of the interrelationship between the reservoirs and natural ecosystems of the region is essential with a view to not only preserve the existing environments but also to further improve its quality. Such goals as the improvement of natural conditions and environments are adequately achieved by the construction of multipurpose reservoirs. The long term use of reservoirs has clearly proved that in a variety of climatic zones, the water reservoirs form the basis of stable ecosystems matched with natural environment. The environmental problems arising from water reservoirs and remedial measures are as given below.

2.5.1 Biological Impact

Some of the major impacts in this category are as follows:

Fish: Free passage of migratory fish to and from their spawning grounds is disturbed due to the obstruction created by the construction of dam. Species and habitat of fish in the downstream river reach are also effected. Creation of reservoir provides conducive environments favouring reproduction of several fish species. The river discharges below the reservoir are higher during dry season than under natural pre-storage condition. This provides for favourable conditions for the development of fisheries in the downstream river reach.

Flora and fauna: Deforestation of the reservoir submerged area and consequent displacement of wild life population is inevitable. Area submerged in a reservoir constitutes an insignificant percentage of catchment area upstream of the dam. Moreover, the mature ecosystems, such as primary forests, are least affected by the reservoir and its surroundings. However, to enhance flora and fauna, it is essential to develop national parks, game reserves, forest reserves and forest management.

Diseases: Reservoirs contribute to the spread of water borne human diseases. Planning for reservoir should include consideration of the water quality standards for every use of water and the control of water quality.

2.5.2 Physical Impacts

Reservoir induced Seismicity: Many people consider reservoirs to trigger earth tremors. While there is no complete agreement on the exact cause of this seismic activity, a general belief is that earthquakes are caused by the filling of reservoir at sites where natural stresses in the underlying rock mass have developed to a state very close to rupture. An important measure is early installation of seismographs to provide information on the seismic potential of the region before construction and monitoring of post-construction behaviour.

Aquatic nuisance plants: Proliferation of nuisance aquatic vegetation is associated with reservoirs. Concern, however, is limited to those aquatic plants which are larger than microscopic algae. Early planning and action can avoid some of the hazards posed by aquatic plants to public health, fisheries and navigation.

Silt: The river water deposits silt into the reservoir which in turn triggers a number of environmental problems. Silting may be reduced by placing outlets in the dam at such points that allow some of the silt to escape to the downstream channel.

It is evident that multipurpose irrigation and flood control projects should take into account, right at the planning stage, appropriate steps for the protection, preservation and development of the environment.

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