International Journal of Innovative Technology & Adaptive Management (IJITAM)
ISSN: 2347-3622, Volume-1, Issue-3, December 2013

RESERVOIR OPERATION

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Synopsis:

Construction of a dam can be undertaken for many purposes, including flood control, power generation, irrigation, livestock watering, fish farming, navigation, and municipal water supply. Some reservoir impoundments are also used for recreation and water sports, for fish and wildlife propagation, and for augmentation of low flows.

Dams can adversely impact the hydraulic regime, the quality of the surface waters, and habitat in the stream or river where they are located. A variety of impacts can result from the construction and operation of these facilities. Operational practices adopted for use of the reservoir will inevitably affect on site impacts and downstream hydrology.

The principles or practices of reservoir operation vary from country to country depending upon the types of reservoirs, catchment's characteristic and requirements.

Concept:

Water, a major natural resource is used for multiple uses as irrigation, power generation, navigation etc., besides industrial and domestic needs. The main source of availability of water is the surface run-off in the forms of rivers. The flow in rivers changes seasonally and from year to year, due to temporal and spatial variation in precipitation. Thus the water available abundantly during monsoon season becomes a scare during the non monsoon season, when it is most needed. The traditional method followed commonly for meeting the needs of water during the scare period is construction of storage reservoir on river course. The excess water during the monsoon season is stored in such reservoir for eventual use in lean period. Construction of storages will also help in control of flood as well as generation of electric power.

Water quantity and quality are considered to be the main driving forces of the reservoir operation. The concept of operation of reservoir considering it as a single entity

International Journal of Innovative Technology & Adaptive Management (IJITAM)
ISSN: 2347-3622, Volume-1, Issue-3, December 2013

has given way to the concept of integrated operation of reservoirs. Application of system engineering methods, such as mathematical optimization and simulation are now being increasingly used for defining, evaluation and selection of reservoir operation policies.

Objectives & Purposes:

Reservoir operation is an important element in water resources planning and management. It consists of several control variables that defines the operation strategies for guiding a sequence of releases to meet a large number of demands from stakeholders with different objectives, such as flood control, hydropower generation and allocation of water to different users. A major difficulty in the operation of reservoirs is the often conflicting and unequal objectives. Therefore, it is necessary to optimise reservoir operation in determining balanced solutions between the conflicting objectives Hydro development is one of the most important mechanisms for mitigating adverse impacts and maximising positive benefits. An appropriate operational strategy will aid environmental management at site and also downstream. Maintenance of adequate flow to meet downstream requirements is a key aspect of the operational strategy. The basis of their operation is to obtain the maximum beneficial use of the available storage. Although reservoirs are not designed to provide complete protection against all possible floods, an efficient use of their storage capacity can reduce flood levels and prevent major flood disasters. The main objective of flood control reservoir operations is to minimize flood damages at downstream locations, while ensuring that the maximum flood control storage capacity of the reservoir is never exceeded.

PRINCIPLES OF OPERATION

The following are some of the common principles of reservoir operation:

Single Purpose Reservoirs

a) Flood Control

Operation of flood control reservoirs is primarily governed by the available flood storage capacity, discharge capacity of outlets, their location and nature of damage centres to be protected, flood characteristics, ability and accuracy of flood/storm forecast and size of the uncontrolled drainage area. The following principles are used for regulation of difficult situations.

i) *Effective use of available flood control storage.*
This principles aims at reducing flood damages of the locations to be protected to the maximum extent possible by effective use of flood control storage capacity available at the time of each flood event.

ii) *Control of Reservoir Design Flood*
Full storage capacity would be utilized only when the flood develops into the reservoir design flood.

iii) *Combination of principles (i) & (ii)*

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The principle (i) is followed for the lower portion of the flood reserve to achieve the maximum benefits by controlling the earlier part of flood. Thereafter releases are made as scheduled for the reservoir design flood as in principle (ii).

iv) *Flood control in emergencies*

Prepare an emergency release schedule that uses information on reservoir data immediately available to the operator.

b) Conservation

Reservoir meant for augmentation of supplies during lean period should usually be operated to fill as early as possible during filling period, while meeting the requirements. All water in excess of the requirements of the filling period is impounded. No spilling of water over the spillway will normally be permitted until the FRL is reach.

Multi-purpose Reservoirs

Operation of multipurpose reservoir should be governed by the manner in which various uses of the reservoir have been combined. To meet the demands of the end users, the priorities for allocation may be used as a guideline. In general five basic zones of reservoir space may be used in operating a reservoir for various functions.

i) *Spill Zone*

Storage space above the flood control zone between FRL and MWL. This space is occupied mostly during high floods and the releases from this zone are trade off between structural safety and D/s flood damages.

ii) *Flood control zone*

Temporary storage embarked for absorbing high flows for allevating d/s flood damages. This should be space emptied as soon as possible to negotiate next flood event.

iii) *Conservation zone*

This storage space is used for conservation of water for meeting various future demands. This zone is generally between FRL and dead storage level.

iv) *Buffer zone*

The storage space above the dead storage level which is used to satisfy only very essential water needs in case of extreme situation

v) *Dead storage zone*

The lowest zone in which the storage is meant to absorbed some of the sediments entering into the reservoir.

OPERATION RULES

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The operation of the reservoir follows a certain procedure so that the competing water users would be able to get their equitable share based on the agreed policy such as the amount allocated to each user. Water allocation is usually dictated by **rule curve** that is derived from historical data of river flows and water demands. A rule curve **shows the minimum water level require**ment **in the reservoir at a specific time to meet the particular needs** for which the reservoir is designed. It is important to note that rule curve shall be followed except during periods of extreme drought and when public interest so requires.

Rule Curve: It is the target level planned to be achieved in a reservoir, under different conditions of probabilities of inflows and/or demands, during various time period in a year.

Upper Rule Curve

The upper rule curve **specifies the uppermost level** up to which a reservoir should be filled if there is sufficient inflow to the reservoir. It can be either **FRL or a level below FRL**. If the reservoir reach this level then the demands for the remaining duration of that year are likely to be satisfied in full. Thus it is most desirable level and effort is made to maintained this level.

Middle Rule Curve

The middle rule curve is **use when water is scarce** and full supply for various demand cannot be made throughout the year. Supply of some demands (with low priority) can be curtailed to some extent so that the partial demands can be satisfied for longer duration.

Lower Rule Curve

The lower rule curve is **critical for water supply demands** and **minimum flow requirements in downstream river**. If the reservoir level falls below this level then supply is made to meet full demands of water supply and minimum flow only. No water is released for irrigation or hydropower generation in this situation.

When the reservoir serves two or more purposes, water allocation becomes more complex. During normal flows, the reservoir will be maintained and kept at the rule curve level. During heavy flows, the water level may be allowed to rise above the rule curve. If exceptionally high inflows are expected, the reservoir is drawn down below the rule curve before the water arrives. If low flow conditions prevail, the reservoir may be drawn down below the rule curve to release the design dependable flow to satisfy the downstream

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needs. During drought periods the reservoir may be completely emptied. Flow regulation is usually dictated by rule curves (derived from historical data of river flows and energy demands) which show storage requirements during a specified period and give guidance for the operation of reservoir from day to day. It is important to note that any rule curve, representing the deficiency between energy requirements and dependable stream flow, is only valid for the load and flow conditions under which the curve was drawn. Moreover, there is always the possibility of encountering lower than recorded reservoir inflows. If a reservoir is operated on the basis of the rule curve derived from historical flow conditions, the result could be an empty reservoir with consequent power shortage. Similarly, during flood seasons, one may run the risk of discharging useable flow.

Reservoir Storage Zones

Multiple-purpose reservoir operation can best be described by dividing total reservoir storage into functional zones. The top zone represents *flood control storage* capacity, which is kept empty except when regulating floods. Below the flood control zone is the *conservation storage zone* or *joint use zone*. This serves various site and downstream water uses, including power generation, irrigation, municipal and industrial water supply, navigation, water quality, fish and wildlife, and recreation. Below the conservation zone is the dead storage zone, which is kept full at all times to provide minimum head for power generation, sedimentation storage space, and other uses.

Downstream

Run-of-River Hydro Project

A run-of-the-river dam is usually a **low dam, with small hydraulic head, limited storage area, short detention time, and no positive control over lake storage**. The amount of water released from these dams depends on the amount of water entering the impoundment from upstream sources.

For a run-of-river hydro project, the stream flow passes through the project without much modification. **Specific flow release** requirements are therefore **not** generally **needed.**

Multipurpose Reservoir Storage

The storage dam is typically a **high dam with large hydraulic head, long detention time, and positive control over the volume of water released from the impoundment.** Dams constructed for either flood control or hydroelectric power generations are usually of the storage class. For reservoir storage plant capable of storing seasonal or yearly floods for hydro generation during low flow season, the plant discharges may still fluctuate

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considerably on a daily basis. In this case, it is desirable to **regulate the minimum flow** and the rate of change in flow releases.

Downstream flow requirements must also be considered for:

- navigation;
- fisheries;
- water quality and waste assimilation;
- aesthetic values;
- flushing to remove sediments from the reservoir and/or streambed downstream;
- flood control (evacuating storage space before flooding);
- replication of beneficial natural floods for flood plain agriculture and prevention of land salinisation;
- downstream channel between the dam toe and the exit of the power plant's tailrace;
- irrigation;
- municipal and industrial water supply (including cooling water supply);
- streamflow required to prevent saline intrusion..

Upstream:

The reservoirs, created by dams on rivers, also get silt in the water of the rivers that enters the reservoirs and a significant proportion of the silt settles down in the reservoir, thus reducing the space available for storage of water. Moreover, studies over the years have shown that the silt gets deposited in both the dead storage (the storage at the bottom, below the Minimum Draw Down Level, which is not used under normal circumstances) and in the Live Storage (LS). This process of accumulation of silt in the reservoirs is called siltation.

Siltation results in reduction in benefits from the projects constructed at huge costs to the nation. Siltations of reservoirs have a number of impacts,

increased evaporation losses,
increased backwater flooding and
damage the power house turbines.

Gregory Morris, (author of Reservoir Sedimentation Handbook, 1997) in a paper presented at the Sixth International Symposium on River Sedimentation in New Delhi in 1995 wrote, "Planned Obsolescence due to sedimentation affects most reservoirs worldwide, not just in India, and will render many of them unusable in the foreseeable future. Dams are uniquely different from engineering infrastructure such as roads, harbors, and cities, and which can be reconstructed on the same site occupied by obsolete infrastructure. Dams cannot be

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reconstructed at the same site once the reservoir has filled with sediment; the sediment must either be removed or the site abandoned. The cost of sediment removal at a large reservoir can easily exceed the original dam construction cost by an order of magnitude." India has by now about 4500 large reservoirs and lakhs of smaller reservoirs. Periodical capacity surveys of reservoir help in assessing the rate of siltation and reduction in storage capacity. This information is necessary for efficient management of the reservoir. Periodical capacity survey of reservoirs in a basin is also necessary to arrive at a realistic siltation index for planning of future reservoir projects in the basin. The trend that siltation is a serious issue and action is required to arrest the destruction of productive reservoir capacity created at such huge costs has been known for many years. Morris, in his paper in 1995 cited earlier had said, "the overall picture indicates that reservoir sedimentation is a serious national problem which requires immediate action…" The Mid Term Appraisal of the 9th Plan had also warned (Oct 2000, p 76), "there is an urgent need to review the status of reservoir sedimentation." However, most such warnings have gone unheeded and catchment area treatment that can help reduce the siltation, has largely remained non existent, except on paper. The Report of the Govt of India's National Commission of Integrated Water Resources Development implies that we are losing about 1.3 BCM of storage capacity each year. That should be alarming enough for everyone as at today's rates creation of 1.3 BCM storage capacity would cost Rs 1448 crores. That means that on an average, each day we are losing Rs 4 crores worth of storage capacity through siltation.

The power generation from the upgraded 15 MW installed capacity at the Gumti Dam in Tripura is so low that even the World Bank strategy paper for the North East (dated June 28, 2006) recommends exploration of decommissioning of the dam.

Reservoirs of high siltation rate in India:

Reservoir	River	Design rate (mm/yr)	Actual rate (mm/yr)
Gumti (Tripura)	Gumti	0.362	9.94
Kallada (Kerala)	Kallada	1.45	4.78
Kadana (Gujarat)	Mahi	0.13	1.146

Siltation Control:

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While it is not possible to totally avoid or stop siltation, one way to reduce the siltation of the reservoirs is to do **Catchment's Area Treatment (CAT).** CAT applies various techniques like plantation, gully plugging, check dams, etc in the degraded portions of the catchments to reduce the silt coming into the reservoirs. CAT plans are expected to be implemented before the project construction is over so that there is minimum siltation of the reservoirs once water storage in the reservoir is started. However here too the situation is alarming.. In case of some like Bhakra, where the project had a CAT component, according to the Govt. of India's Comptroller and Auditor General, there was not way to ascertain if any CAT had really been done on ground, while the money allocated for the CAT was all spent, indirectly hinting that nothing was really done. Most recent examples are the World Bank funded 1500 MW Nathpa Jhakri Hydropower Project and the Jaiprakash Group's 300 MW Baspa project, both in Himachal Pradesh. Both projects were commissioned in 2003, but, the CAT plans are yet to be implemented. Nathpa Jhakri project is already facing serious problems due to this as the project had to be stopped due to high silt in the river for 25 days since April 2006 alone.

The operation of dams can also generate a variety of types of nonpoint source pollution in surface waters. Controlled releases from dams can change the timing and quantity of freshwater inputs into coastal waters. **Dam operations may lead to** reduced downstream flushing, which, in turn, may lead to **increased loads of BOD, phosphorus, and nitrogen; changes in pH; and the potential for increased algal growth.** Lower instream flows, and lower peak flows associated with controlled releases from dams, can result in sediment deposition in the channel several miles downstream of the dam. The tendency of dam releases to be clear water, or water without sediment, can result in erosion of the streambed and scouring of the channel below the dam, especially the smaller-sized sediments. Dams also limit downstream recruitment of suitably-sized substrate required for the anchoring and growth of aquatic plants. Finally, reservoir releases can alter the water temperature and lower the dissolved oxygen levels in downstream portions of the waterway.

Impact on Socio-Economic Growth

Water resources development means exploitation of water for benefiting the society by meeting the basic needs of individuals. Food and energy are the two basic requirements for sustenance and economic development of a region, which are possible through the utilization of water resources for irrigation and power. The following are the impact on Socio-Economic Growth as a result of proper utilization of water resource projects.

Agricultural Growth

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Power growth

Industrial Growth

Social Growth

Flood Control Reservoir Operation adopted in USA

A common practice in reservoir operations is to develop emergency operation schedules (EOS). These **schedules are decision tools that provide guidance to reservoir operators in charge of making real-time release decisions during major flood events.** Optimum release decisions would result in full use of the available storage while ensuring that the storage capacity is not exceeded. Such a theoretical optimum is only possible with perfect knowledge of future inflows. The methodology currently used by the U.S. Army Corps of Engineers (USACE) for developing EOS dates back to 1959 (USACE 1959). This methodology, although theoretically sound, is based on a series of simplifying assumptions regarding future flows. **The required releases to limit the storage to the capacity available are determined based on estimating the minimum inflow volume expected during the remainder of a flood**. This volume is obtained by assuming that the inflow hydrograph has just crested and computing the volume under the recession limb of the hydrograph. For conservatively low inflow volume estimates, the assumed recession is made somewhat steeper than the average observed recession. The primary objective of this study is to devise an alternative methodology for developing EOS. As opposed to the USACE approach, the proposed methodology deals with uncertainties regarding future inflows by considering them as a stochastic process. Stochastic streamflow generation models provide the capability of analyzing statistical probabilities of the expected inflow volumes conditional to the current streamflow conditions and time of year. This analysis allows formulating a series of alternative risk based EOS in which the reservoir releases, specified as a function of reservoir levels, inflows, and time of year, are associated with a certain risk of failing to attain the emergency operations objectives. It is envisioned that this series of schedules will provide a wider and more flexible decision framework for reservoir operators in which risk may be taken explicitly into account.

Flood Control Reservoir Operations

The key variables governing the operation of flood control reservoirs are: (1) the available (or residual) storage capacity, and (2) the expected volume of inflow from an incoming flood. Although the residual storage is always known, the uncertainty regarding the expected inflow volumes makes reservoir regulation a challenging task. The

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method of operation of a reservoir is the most important factor in insuring the realization of the benefits that justified construction of the project (USACE 1959).

Normal Operations

The normal operations scheme is **based on the concept of reducing damaging stages at downstream control points during a single flood event with the currently available storage capacity** (USACE 1987). This approach disregards the possibility of having a substantial portion of the flood control storage filled upon the occurrence of a large subsequent flood. Provided that the expected inflow volume will not exceed the available storage capacity, releases are based on the maximum allowable non-damaging channel capacity at downstream control points. Every effort must be made in actual operations to use the full channel capacity in order to attain maximum flood control benefits (Beard 1963). During normal non-flooding conditions, the outlet works are set to pass the inflows in order to maintain an empty reservoir. Whenever significant rainfall occurs or it is expected to occur, the outlet works are closed and they remain closed until it is evident that the flood has crested and downstream conditions are below non-damaging levels. The traditional approach of the post-flood evacuation process is to make releases that will empty the reservoir as quickly as possible without contributing to flows at downstream control points exceeding the channel capacity. For systems of flood control reservoirs protecting a joint downstream location, their combined releases should not exceed the established maximum channel capacity at common control points. Release decisions are based on maintaining equal available flood storage in each reservoir. Thus, releases are made from the reservoir with the greatest percentage of used storage. Other balancing configurations are possible, however, depending on the characteristics of the system.

Another important consideration when making release decisions is the runoff contribution from uncontrolled areas. If control points are located at relatively far distances, allowance must be made for any runoff from the uncontrolled watershed areas below the dam. This runoff could account for a significant portion of the allowable channel capacity. If rainfall occurs after a release has been made but within the water travel time to a control point, reservoir releases may combine with the uncontrolled runoff and cause downstream flooding. This runoff must be forecasted, a possible forecast error added, and the resulting quantity deducted from the allowable channel capacity in order to determine appropriate reservoir releases (Beard 1963). Accurate rainfall and runoff forecasts are essential for this aspect of reservoir operations. Following the normal operation scheme typically results in maximizing the use of the available flood storage. However, it may also result in prolonged retention times of the stored volume if releases are controlled by stringent downstream constraints. Furthermore, reservoir releases may be reduced by extraneous circumstances that interfere

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with normal operations. If a reservoir experiences multiple flood events over periods which are not long enough to drain the reservoir to safe levels, the reservoir stage can gradually increase to critical levels due to the cumulative effect of the multiple floods, even though no single large flood event may have occurred. In any event, if a major flood occurs while there is a limited amount of flood control storage capacity, operation is switched over to emergency operations, wherein a fixed schedule of releases is followed to assure greater control of the flood event (USACE 1987).

Emergency Operations

EOS are decision tools typically in the form of a family of regulation curves that expresses reservoir releases as a function of reservoir state (i.e. reservoir inflows and storage level). These schedules do not depend on rainfall and runoff forecasts, downstream flooding conditions, or any other data external to the reservoir itself. **These schedules are considered as guides to be used by reservoir operators during critical floods** with variation there from to be based on additional hydrologic information, if advisable. Moreover, communications between the reservoir operator and the control center may be interrupted during emergency conditions. Thus, emergency schedules are convenient as they can be used in complete isolation at the dam site. The **top priority under emergency operations is ensuring that the embankment is never overtopped**. As opposed to normal operations, **release decisions are based on the current reservoir state, not on downstream conditions**. Therefore, flood stages may be exceeded at some locations so that the reservoir will not be completely filled before the entire flood has passed. The basis for this approach is that moderately high damaging releases beginning before the flood control storage is full are considered preferable to waiting until a full reservoir necessitates much higher releases to avoid overtopping. It is highly important that the necessary releases are made as soon as possible because even a minor delay in releases can result in a major increase in storage requirement (Beard 1963). However, reservoir releases must be increased gradually in order to prevent undue damage downstream.

The consequences of exceeding the storage capacity of a reservoir are typically far worse than making pre-releases early in a flood event to provide the additional storage required to accommodate the remainder of the flood. Pre-releases are critical when operating reservoirs with a limited amount of flood control storage capacity. **If the storage capacity is exceeded, flood damages will occur both upstream and downstream of the reservoir**. The excessive water elevation in the reservoir will cause upstream flooding, and uncontrolled releases through emergency spillways will aggravate downstream flooding. Furthermore, the reservoir operator needs to consider that the dam itself represents an additional risk, although small, to dam break by overtopping. A dam break would cause

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damages to the protected region that would greatly exceed those produced by the flood alone under natural conditions. Although the primary objective is the protection of the dam, maximizing the use of the flood control storage is also desired. This secondary objective aims for the maximum possible protection of downstream regions, which is typically the primary reason that justified construction of the project. Ideally, the required emergency release rate for a given reservoir state is that which, if held constant during the remainder of the flood, will exactly fill the residual flood control storage, thereby fully satisfying both objectives. If emergency releases are not made assuming that the storage capacity will not be exceeded and later inflows continue increasing, even larger releases will be needed to avoid overtopping and damages downstream will be greater than if moderate releases were made earlier. On the other hand, if emergency releases are made but the actual inflow volume was smaller than expected, the excessive releases will result in a portion of the flood control storage not being used during the flood. This situation could bring several complaints or even lawsuits from downstream dwellers since damaging releases were made even though the reservoir never reached its full capacity. Nonetheless, the risk of such situation during emergency conditions needs to be accepted to some extent considering the adverse consequences of dam overtopping.

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