TRAINING COURSE

ON

RESERVOIR OPERATION

(UNDER WORLD BANK AIDED HYDROLOGY PROJECT)

Module 4

Reservoir Operation
Using
Rule Curves

BY

S K Jain, NIH
M K Goel, NIH

NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA

RESERVOIR OPERATION USING RULE CURVES

1.0 INTRODUCTION

Reservoirs are an important component of many water resources development projects. The principal function of a reservoir is to equalize the natural streamflow and to change the temporal and spatial availability of water in accordance with the requirement of mankind. In India, because of the high time variability of rainfall and uncertain nature of monsoon, it is imperative to utilize the available water resources in optimal and efficient manner. The efficient use of water resources requires not only judicious design but also proper management of reservoirs. A number of generalized approaches like SLOP, Rule curves and storage zoning etc. are available for reservoir operation. Here, the regulation of reservoirs using rule curves and the method of deriving rule curves is described.

2.0 DEFINITION OF RULE CURVE

The rule curve specifies the ideal storage or empty space to be maintained in a reservoir during different times of the year. The implicit assumption is that a reservoir can satisfy its purposes to the maximum possible extent if the storage levels or empty space specified by the rule curve are maintained in the reservoir at different times. The rule curve, as such, does not give the amount of water to be released from the reservoir. This amount will depend upon the actual inflows to the reservoir. However, it provides guidance for daily operation of a reservoir.

The rule curves are generally derived by operation studies using historic flows or generated flows where long term historic records are not available. Sometimes, it is not possible to stick to the rule curve with respect to storage levels. It is possible to return to the rule curve in several ways. One way 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 the safe carrying capacity of the downstream channel if the deviation is positive.

3.0 DERIVATION OF RULE CURVES

The derivation of rule curves depend on the type of the reservoir and the purposes of the reservoir. A reservoir may be classified either as a seasonal reservoir or a multi- annual reservoir. The storage of a seasonal reservoir is required to carry water from wet season to the dry season, whereas multi-annual reservoir storage requires the carry-over of water from a wet period to a subsequent dry period, may be several years later. Similarly, for different purposes like water supply for domestic and industrial use, irrigation, hydropower generation and for flood control, different rule curves may be developed. The derivation of rule curves is described in the following:

3.1 Rule Curve for Reservoir with Seasonal Storage

First of all, a simple case of a reservoir with seasonal storage serving for conservation needs is considered. A reservoir with seasonal storage does not remain full at all times of the year. Further, if the reservoir is able to meet the demands during the critical year, it will be able to serve its purpose for all other years.

In Fig.1(a), the streamflow of a river during the driest year on record and the water requirements have been plotted. Let us assume that at time A, the reservoir is full. From A to B, the demands exceed the natural inflow and hence the contents of the reservoir will be depleting. The mass curve of inflow and demands have been plotted in Fig. 1(b). From time at A onwards, the inflow and demand curves diverge and the difference is maximum at E. This represents the required storage capacity. Now, in Fig.1(b), at point C, the reservoir is empty. From this point, the demand curve is plotted backwards in time and curve CE is obtained which is curve AB lowered and extended to the left. The vertical ordinates between the inflow mass curve EAC and demand mass curve EC represent the volume of water which is in storage during the period from E to C. These vertical ordinates have been plotted against time in Fig. 1(c) and the resulting curve is the rule curve. This rule curve represents the accumulation, in reverse order of time, of the

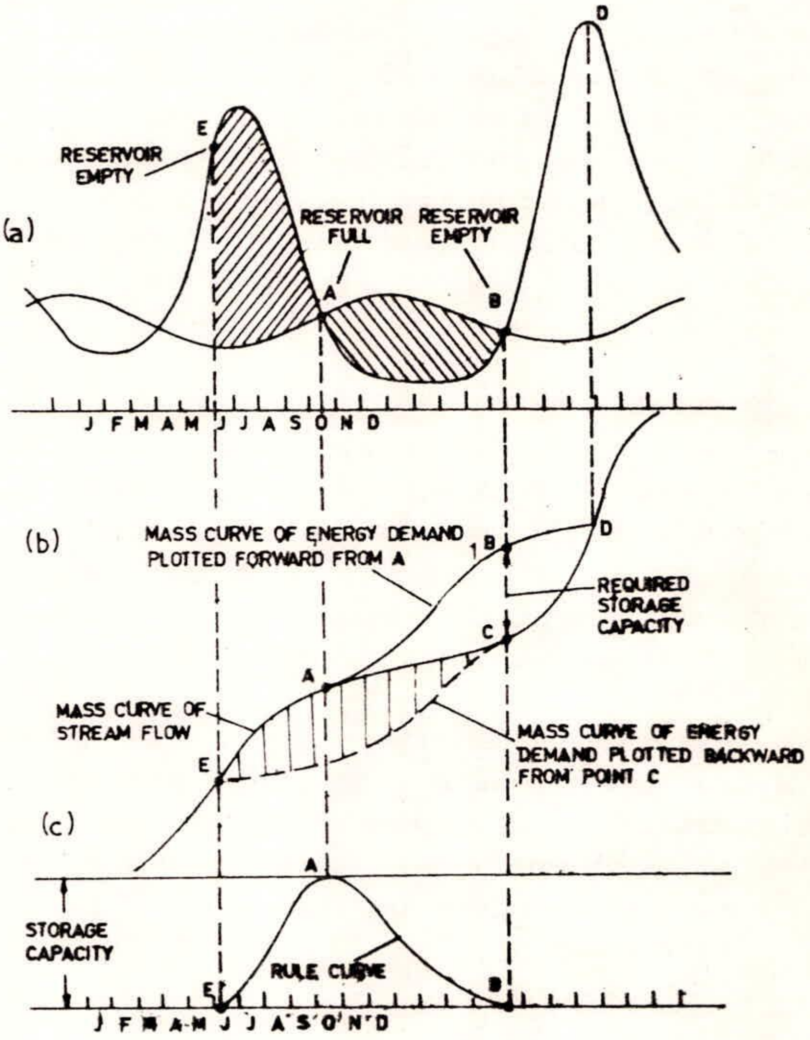


Fig. 1 Development of Rule Curve for Conservation Purpose

deficiency between demands and available streamflow during the critical period. Since it has been assumed earlier that this analysis is being done for the driest year on record and reservoir is of adequate capacity, it can be concluded that whenever there is more water in the reservoir than specified by rule curve, there is no danger of subsequent failure of the reservoir.

Since a rule curve depends on the flow pattern in a critical year, rule curves for other near-critical years should also be prepared. It is possible that these rule curves cross one another at places. Finally, an enveloping curve, some distance above the deficiency curves, should be drawn to guard against streamflow conditions that would be worse than recorded.

3.2 Rule Curve for Reservoir with Multi-annual Storage

For reservoirs designed for multi-annual storage, the operation policy is based on long term targets. Streamflows of a river for the most critical period of record have been plotted in Fig.2(a) along with the conservation use requirements. It is seen from the figure that water has to be stored

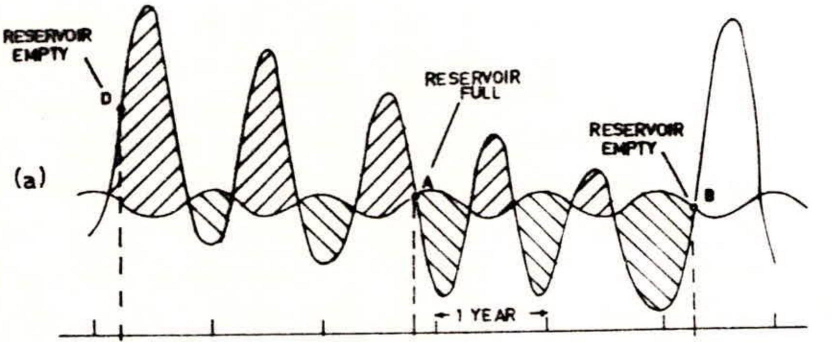


Fig. 2 Development of Rule Curves With Multi-annual Storage

over a period of several years and a carry-over storage is required as the water is carried over from one year to another. The reservoir will be full at time A and thereafter, passing through various stages will become empty at B. The mass curve of streamflows and the demands are plotted in Fig. 2(b). The ordinate BC represents the required reservoir storage. Starting at point C and working to the left, if we plot the mass curve of demands, the ordinate between the mass curve of streamflows and the mass curve of demand represents the required storage capacities, at any time, antecedent to the end of the critical period. These ordinates are plotted on a horizontal base in Fig. 2(c). Since the curve obtained is spread over several years, we have to take the year with the highest ordinates in order to find the appropriate rule curve. This exercise is repeated for other critical flow periods to obtain similar type of curves from A to B. Now these curves are screened month by month and the highest deficiency points are chosen. An envelope curve can be drawn using these points which is the required rule curve.

4.0 DERIVATION OF INITIAL RULE CURVES

Rule curves for different purposes can be derived separately and the regulation of the reservoir using different rule curves can be carried out. The procedure is described as follows:

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

4.1 Trial Rule Level Computation for Highest Priority Demands

Rule level for highest priority demands like water supply for domestic and industrial purposes, minimum flow requirements etc. is calculated assuming the following conditions:

a) Reservoir level reaches to dead storage level by the end of the water year.
b) 90% reliable inflow (very low amount of inflow) is entering the reservoir.
c) Only highest priority demands are being satisfied.

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

$$\text{Storage}_{begin} = \text{Storage}_{end} - \text{Inflow} + \text{Demand} + \text{Evaporation} \qquad ...(1)$$

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

4.2 Trial Rule Level Computation for Other Demands

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

a) Reservoir level reaches to dead storage level by the end of the water year.
b) 75% reliable inflow is entering the reservoir.
c) Full conservation demands from the reservoir are being satisfied.

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

4.3 Calculation of Uppermost Rule Level

All the rule curves calculated above are derived for critical situations so as foresee the critical conditions in the reservoir and to timely regulate the supply of water. The uppermost rule levels are calculated for the case when there is sufficient inflow in the reservoir. Though it is most desirable to fill the reservoir up to FRL, sometimes, it is required to spill water from the reservoir top and spill from the reservoir should be made off and on to keep up the downstream channel and to avoid encroachment in the river bed. The conditions which are presumed for deriving upper rule curve are:

a) Reservoir level is at FRL after the end of monsoon period.
b) 50% reliable inflow is entering the reservoir.
c) Full conservation demands from the reservoir are being satisfied.

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

$$\text{Storage}_{\text{end}} = \text{Storage}_{\text{begin}} + \text{Inflow} - \text{Demand} - \text{Evaporation} \qquad \ldots(2)$$

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

4.4 Steps For Deriving Rule Curves

Following steps, in order of sequence, should be executed for finalizing the rule curve levels.

1. Determine the projected demands for the period for which, it is required to derive the rule

curves.

2. Obtain other data as evaporation depths, inflow series at the dam site, dead storage level and full reservoir level.
3. Carry out the probability study and find out the inflow values corresponding to different probability levels as 50%, 60%, 70%, 75%, 80% and 90%.
4. For deriving various rule levels, assume the initial conditions in the reservoir as described previously and decide the probable inflow values to be used.
5. Use either the forward or backward calculation method, depending on the purpose of the rule curve.
6. After deriving the initial rule curve levels, carry out the simulation study with the observed inflow record and observe the performance of the reservoir.
7. Based on the observation of the operation table, modify the rule levels till satisfactory performance of the reservoir is achieved.

5.0 OPERATION OF A RESERVOIR USING RULE CURVES

When the reservoir level, at any time, is above the elevation of the rule curve as of the same time, the water that can be supplied for meeting all conservation demands, is released from the reservoir. When the available storage is only slightly above, or equals the critical storage capacity indicated by the rule curve, the release of water should be restricted to such a quantity that the reservoir storage does not fall below the rule curve. The lower limit of the release is, of course, the minimum requirement with respect to various demands, as of that time period. When for some reason, the level in the reservoir drops below the rule curve, the release should be limited to the minimum requirements, with the object of returning as soon as possible to the rule curve.

The operation of a reservoir by strictly following the rule curves becomes quite rigid. Many times, due to various conditions like low inflows, minimum requirements for demands etc., it is not possible to stick to the rule with respect to storage levels. A reservoir operation schedule for reservoirs with adequate forecasting system for streamflows and precipitation is termed as flexible schedule. This flexible operation requires use of better models and careful planning and use of computers. However, the significant amount of larger benefits which can be derived by the flexible schedule makes it imperative to use them for major reservoirs particularly when the resource availability is limited and allocation has to be done among a number of competing users. In order to provide flexibility in operation, different rule curves are developed in different circumstances. Some other operation policies followed in these circumstances are described below.

5.1 Some Operating Policies

These operational policies, which are developed by intuition are anticipatory in character and are quite useful in the case of single purpose single reservoir or multiple reservoirs as the case may be. These are useful specifically to municipal water supply reservoirs wherein conservation of water is the sole objective. The rules are different for series or parallel configuration of reservoirs.

a) Reservoirs in series : The operating rule in this case is that downstream releases are met by the immediately upstream reservoirs till it is completely drawn down and before using any upstream reservoirs.

In the Fig. 3, releases D_2 and D_3 are to be met from reservoir 2 till it is completely drawn down. When it is not possible to meet the demand D_2 and D_3 from reservoir 2, then only water from reservoir 1 is to be released to meet the demands D_2 and D_3. This rule makes use of available storage fully and ensures conservation of avoidable spills from downstream reservoirs.

b) Reservoirs in Parallel : In this configuration two procedures are commonly used. The first involves discharging water first from reservoirs with relatively larger drainage areas or potential inflows per unit storage capacity.

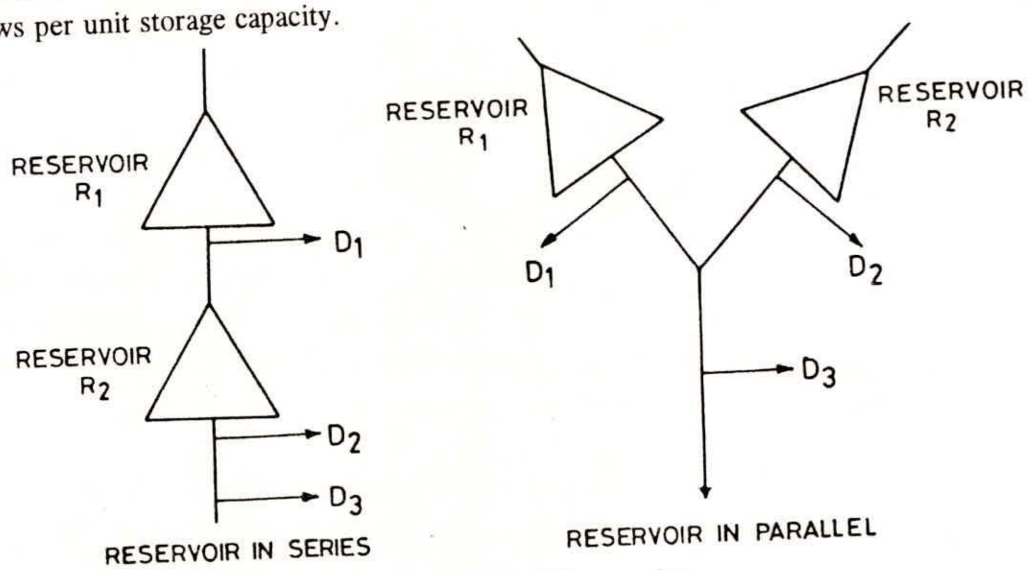


Fig. 3 Configuration of Reservoirs

In the Fig. 3, the drainage areas to storage volume capacity ratios for two reservoirs are compared (assuming the runoff per unit of drainage area is same). The reservoir with the larger ratio is used to supply diversion D_3 before the other reservoir is drawn down. Discharging water first from the reservoir having the largest drainage to storage volume capacity ratio will usually result in a reasonable conservation of water.

Space Rule

A more precise procedure involves drawing in tandem from each reservoir. This requires monitoring storage volumes and estimating future inflow. Such a policy minimizes expected water wastage. The latter rule is referred to as a space rule. In terms of probability when parallel reservoirs are operated by this rule, the objective is to equalize the probability that the reservoirs will have filled at the end of drawn-down refill cycle. Actually all the reservoirs will be full and spilling, full and not spilling, or partly full, the unoccupied storage space being proportioned to inflows during the drawdown refill cycle.

$$\sum_{j}^{m} \frac{S_{\max j} - S_{ijk} - Q_{jk} + R_{jk}}{(S_{maxj} - S_{ijk} - Q_{jk}) + R_T} = \sum_{j}^{m} \frac{Q_{i,n}}{Q_{j,n}} \qquad \ldots(3)$$

Where S_{maxj} is the full capacity of the j^{th} in a series of m parallel reservoirs; S_{ijk} is the initial contents of the j^{th} reservoir in the k^{th} of a series of n months; Q_{jk} is the flow into j^{th} reservoir in the k^{th} month; R_{jk} is the release from the j^{th} reservoir in the k^{th} month; R_{jk} is the sum total of releases required to fulfill target outputs; and $Q_{j,n-k}$ is the prescribed flow into the j^{th} reservoir for the remaining n-k months of the drawdown refill cycle. We can solve the above equation for R_{jk}, the release from the j^{th} reservoir in the k^{th} month.

$$\begin{aligned} R_{jk} = S_{ijk} + Q_{jk} + [\sum_{j}^{m} (S_{\max j} - S_{ijk} - \\ R_T] (Q_{j,n-k} / \sum_{j}^{m} Q_{j,n-k}) - S_{maxj} \end{aligned} \qquad \ldots(4)$$

Subject to the constraint $0 < R_{jk} < (S_{ijk} + Q_{jk})$

The space rule is very useful for situations where inflow forecasting is very reliable as in the case of runoff from snowmelts. For other types of streamflows the effectiveness of the space rule would be a function of the coefficient of variation of the mean monthly flows, the correlation between flows on adjacent streams and the reliability of flow forecasts.

In modified form the space rule can also be used to apportion releases among reservoirs for flood control, based on 6-hr or other short intervals of time. It is valid too, when each unit of water is of equal value in a given reservoir but not of equal value in different reservoirs. However, the space rule must be modified in form to deal with this situation. Unequal values of water are created in a system for instance when a fixed head power plant downstream from reservoir B generates firm energy from irrigation releases, but no such plant exists below reservoir A. In an application of the modified space rule, the economic value of system output was maximized by preventing or minimizing spills of the higher valued water from reservoir B at the expense of spills lower valued water from reservoir A. Had the water within either of the two reservoirs not possessed a fixed value, (as in the case of variable head power plant) application of the rule would have become much more difficult.

Pack Rule

The Pack rule makes use of the streamflow forecasts and tries to avoid spills by additional releases of water in advance (say for dump energy generation). The Pack rule is so called because the possible future spill is packed as tightly as possible into future space turbine capacity. In mathematical terms :

$$R_d = Q_{n-k} - (S_{max} - S_{TK}) - P_{n-k} \qquad \ldots(5)$$

where R_d are the additional releases for the current month, k, for the generation of dump energy; Q_{n-k} is the predicted flow into the reservoir for the remaining (n-k) months of the drawdown refill cycle; S_{max} is the full reservoir capacity; S_{TK} is the reservoir contents in the current month after current flows have been added and releases made to meet the target output for energy and P_{n-k} is the useful water capacity of the turbines for the remaining n-k months of the drawdown refill cycle. If the right hand side of the equation is not positive $R_d = 0$ and the equation is further subject to constraint $P_c - R_d \leq S_{TK}$ where P_c is the useful water capacity of the turbines in the current month after releases have been made through turbines to meet the target output for energy. Predictions as they are seldom perfect that the reservoir may not refill or spill. The pack rule is illustrated through the Fig. 4.

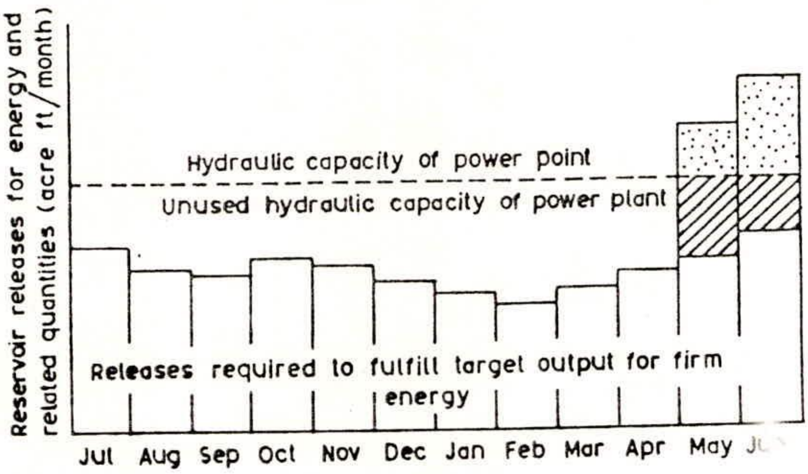


Fig. 4a Pack rule is not applied. Spills occur because dump energy is generated only during months of May and June when reservoir is overflowing. Shaded areas represent dump energy released and dotted areas represent spills.

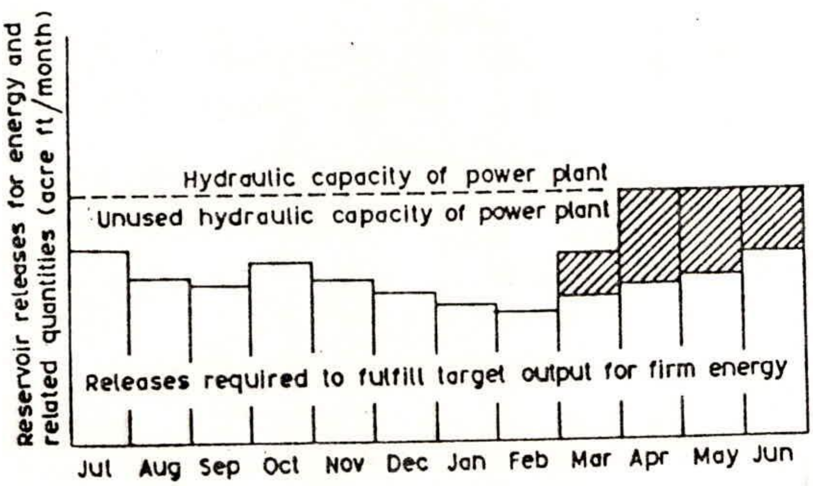
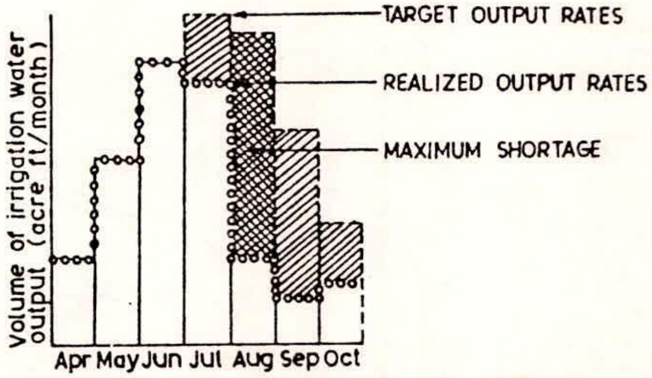


Fig. 4b Pack rule is applied through explicit releases in March and April for generation of dump energy inanticipation of end-of-cycle surpluses in May and June. Shaded areas represent packed dump energy releases during these months.

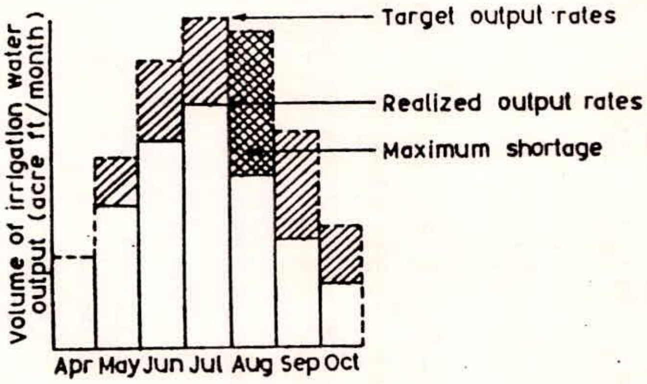
Pack rule can be applied whenever releases beyond specified output requirements are of value. The rule can be of assistance in making decision involving time for simple systems or for parts of complex systems, it can not be used to apportion water among purposes of reservoirs.

The Hedging Rule

The concept of hedging is to distribute, the shortage if anticipated, uniformly so that the intensity of shortage is minimized. It is sometimes economical to accept a small current deficit in output so as to decrease the probability of a more severe water or energy shortage. The Hedging rule is demonstrated through the Fig. 5.



Monthly outputs and shortages without hedging



Monthly outputs and shortages with hedging

Fig. 5 Effect of Hedging Rule on irrigation output. Realized outputs are the same but shortages differ in intensity

Economically a hedging rule can be justified only if the proposed uses of water have nonlinear loss functions. If the marginal values of water for specific uses are constant, the economic losses from shortages must be linear and, because streamflows are stochastic, it follows that it is optimal to postpone shortages as long as possible, in spite of a high probability of a severe deficit later. Therefore, an assured full supply now is preferable to a definite deficit now with a lesser probability of a heavy deficit later. If severe deficit are penalized proportionately more than mild deficits, however, it may pay to reduce the probabilities of suffering heavy deficits.

6.0 RESERVOIR OPERATION DURING FLOOD

Flood control reservoirs are designed to moderate the flood flows that enter the reservoirs. This is achieved by storing a part of inflows in the reservoir and making releases so that the damages in the downstream areas are minimum. The degree of moderation or flood attenuation depends upon the empty storage space available in the reservoir when the flood impinges it. The normal mode of operation of reservoir during floods is to make releases equal to the inflows up to outlet capacity and once the inflows exceed the outlet capacity the reservoir will build up above the full reservoir level (FRL) and the releases would be uncontrolled. The expected rise of the reservoir is up to a level called maximum water level (MWL) which is normally higher than the FRL. The zone between the FRL and MWL is exclusively reserved for flood control.

There may be situations when it is not desirable for reservoir level to rise above full reservoir level. In that situation the outlet capacity to be provided is very large and should be greater than or equal to maximum expected inflows. An alternative to this situation is to make pre-releases in case of expected floods and lower the level of reservoir before the flood impinges. This situation involves use of forecasts of inflows and therefore the confidence of the operator in making pre-releases depends on the reliability of forecasts available.

There can be a third situation where at the beginning of operation of reservoir for flood control the reservoir is not at full reservoir level but is below that level. In such a situation the operator has an option of lowering the reservoir level by pre-releases and utilize the storage space available at the beginning of the operation and additional storage space made available by pre-releases. The operation could be carried out in such a manner that during the passage of the flood the reservoir level reaches the maximum permitted level and thereafter post releases can be made in such a manner that the reservoir comes back to the level from where it started. If not constrained by other factors this approach perhaps involves making most efficient use of the reservoir storage space.

In case of 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.

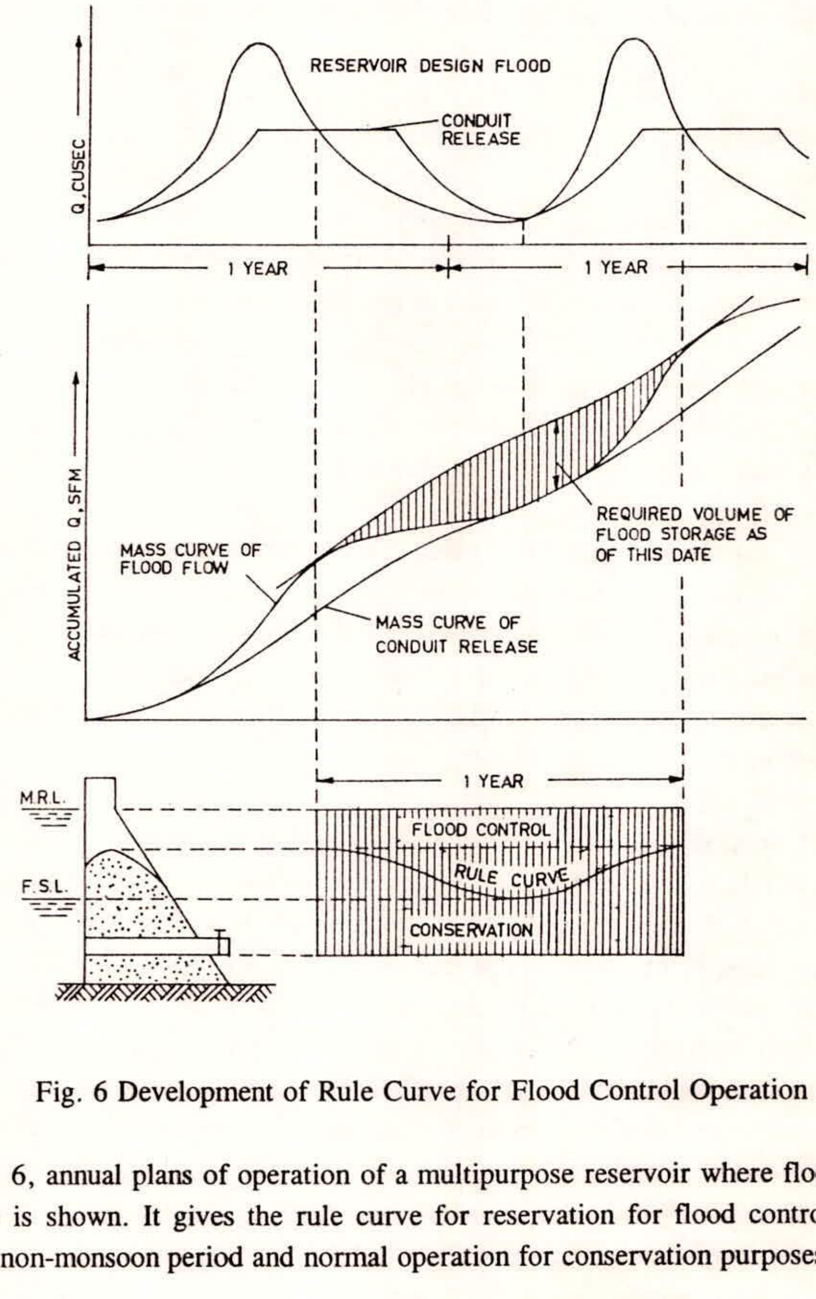


Fig. 6 Development of Rule Curve for Flood Control Operation

In Fig. 6, annual plans of operation of a multipurpose reservoir where flood control is one of the purpose is shown. It gives the rule curve for reservation for flood control storage during monsoons and non-monsoon period and normal operation for conservation purposes for later part of the year.

7.0 DRAWBACKS OF RULE CURVE BASED OPERATION

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

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

[illegible] REFERENCES

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