Multipurpose Reservoir Operation

Introduction

Reservoir operation is an important element in the field of water resources planning and management. Different objectives, such as flood control, hydropower generation and water allocation to different users are satisfied by utilizing several control variables in order to define the operation strategies for guiding a sequence of releases to meet the demands. Often, these objectives are conflicting and unequal, which makes reservoir operation a difficult task. Therefore, balanced solutions between the conflicting objectives are needed to optimise reservoir operation.

In this lecture, we will introduce the common purposes of reservoirs, planning of multi-purpose reservoirs and formulation of multipurpose single and multiple reservoir systems.

Combinations of multipurpose reservoir

For effective utilization of water, some of the purposes are combined often. The preferred combinations are:

(i) Irrigation and power

(ii) Irrigation, power and navigation

(iii) Irrigation, power and water supply

(iv) Recreation, fisheries and wild life

(v) Flood control and water supply

(vi) Power and water supply

(vii) Flood control, irrigation, power and water supply – most common combination.

Planning of multipurpose reservoir

The various purposes of a reservoir may not be compatible to one another. Hence, the unique feature of multipurpose design is an operation plan which effectively compromises the various purposes. There are two possible extremes in reservoir storage allocation:

(i) No storage is jointly used

(ii) All storage is jointly used

In the first case, the total storage requirement is the sum of storage requirements from all purposes. This can be economically obtained when the unit cost of storage is constant or the unit cost decreases as the total storage increases. The second case gives maximum economy since the storage required is not greater than that necessary for any one of the many purposes. Usually a multipurpose reservoir is designed in between these extremes.

Reservoir operating policies typically divide the storage capacity into several pools according to the intended purposes. A typical reservoir pooling for multipurpose is shown in figure 1.

Water in the inactive pool or dead storage is not utilized for any purpose. It serves as a head for hydropower generation, recreation, fish habitat or sediment reserve. Conservation storage purposes include municipal and industrial water supply, irrigation, hydroelectric power, navigation etc. Flood control pool remains empty, except during and immediately after a flood event. The operation procedures include emptying the flood control pools as quickly as possible after a flood event, so as to be prepared for accommodating next flood. The releases should be made by ensuring not to cause downstream flooding. Surcharge pool is the uncontrolled storage capacity above the flood control pool.

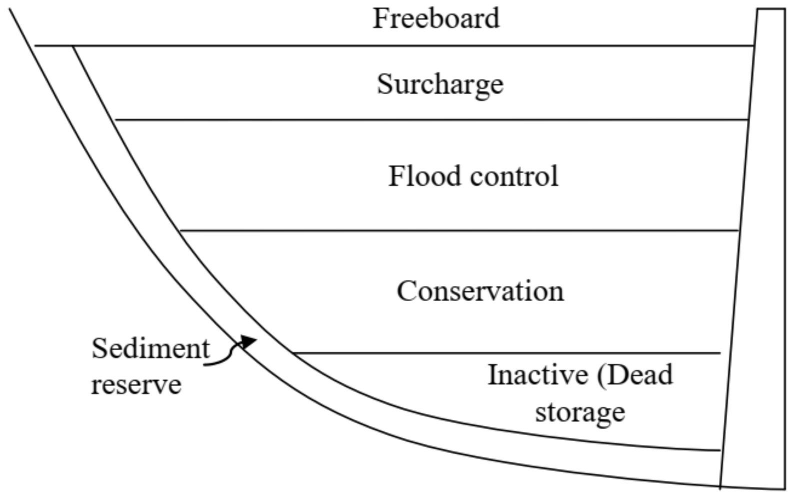

Fig.1 Pooling of reservoir storage

Formulation of Multi-purpose Reservoir System

(i) Optimal sizing and Operation of a single multipurpose reservoir

Consider a multipurpose reservoir designed for water supply, irrigation and power generation and recreation as shown in figure 2. The optimization problem here is to determine both the capacity and operation of the reservoir that maximizes the annual net benefit. The primary decision variables are the reservoir storage and the releases at particular periods to various needs.

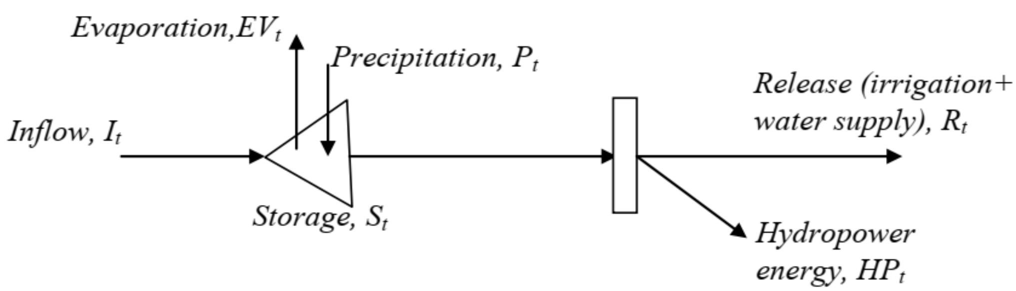

Fig. 2 Multipurpose reservoir

The objective function can be expressed as

$$\text{Maximize } NB = \sum_i \left\{ B_i(T_i) - \sum_t \left[L_{i,t}(D_{i,t}) - G_{i,t}(E_{i,t}) \right] \right\} - C(K)$$

where NB is the annual net benefit, $B_i(T_i)$ is the benefit from target allocation T_i to i^{th} user. $D_{i,t}$ and $E_{i,t}$ are the deficit and excess with respect to T_i for user i in period t. The corresponding loss and gain functions are $L_{i,t}$ and $G_{i,t}$. $C(K)$ is the annual cost for the reservoir of capacity K.

The typical constraints in a reservoir optimization model include conservation of mass and other hydrological and hydraulic constraints, minimum and maximum storage and release, hydropower and water requirements as well as hydropower generation limitations.

(i) Hydraulic constraints as defined by the reservoir continuity equation:

$$S_{t+1} = S_t + I_t + P_t - EV_t - R_t \qquad \text{for } t = 1,2,\ldots,N$$

where S_{t+1} is storage at time step t+1; S_t is storage at time step t; I_t is the reservoir net inflow at time step t (including reservoir inflow, precipitation and evaporation); R_t is the reservoir outflow at time step t. N is the total number of time steps in the considered period.

(ii) Constraints on total discharge and releases for various purposes

$$R_t = R_{irr,t} + R_{ws,t} + R_{ins,t} \qquad \text{for all t}$$

$$R_{hp,t} = R_{ins,t} \qquad \text{for all t}$$

where $R_{irr,t}$, $R_{ws,t}$, $R_{ins,t}$ and $R_{hp,t}$ are releases for irrigation, water supply, instream flow requirement and power generation respectively. These relations are problem specific.

(iii) Reservoir capacity

$$S_t \le K - K_d \qquad \text{for all t, where } K_d \text{ is the dead storage}$$

(iv) Target allocation for irrigation

$$R_{irr,t} + D_{irr,t} - E_{irr,t} = T_{irr,t} \qquad \text{for all t.}$$

(v) Target allocation for water supply release

$$R_{ws,t} + D_{ws,t} - E_{ws,t} = T_{ws,t} \qquad \text{for all t.}$$

(vi) Target allocation for instream flow release

$$R_{ins,t} + D_{ins,t} - E_{ins,t} = T_{ins,t} \qquad \text{for all t.}$$

(vii) Target allocation for power supply

$$\xi \; R_{hp,t} \; h(K_d + S_t, K_d + S_{t+1}) + D_{hp,t} - E_{hp,t} = T_{hp,t} \qquad \text{for all t.}$$

where ξ is the plant efficiency.

(viii) Target allocation for recreation

$$K_d + S_t + D_{rec,t} - E_{rec,t} = T_{rec,t} \qquad \text{for all t.}$$

(ii) <u>Optimal sizing and Operation of a multiple reservoir systems</u>

Consider a three reservoir system in figure 3 which all reservoirs are multipurpose. The purposes are same as those of the previous problem. The hydropower generation is done by taking advantage of the head drop. No additional release is made for generating hydropower. The objective is to maximize the net benefit by determining the optimal capacity and release policy of each reservoir.

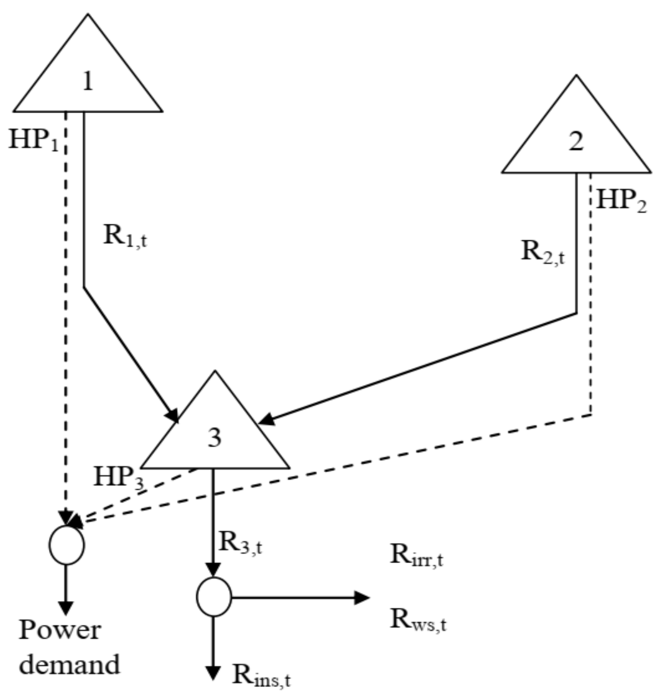

Fig. 3 Three reservoir system

The objective function for this optimization model is

$$\begin{aligned}
\text{Maximize } NB = \quad & \sum_t B_{irr,t}\left(R_{irr,3,t}, T_{irr,3,t}, D_{irr,3,t}, E_{irr,3,t}\right) \\
& + \sum_t B_{ws,t}\left(R_{ws,3,t}, T_{ws,3,t}, D_{ws,3,t}, E_{ws,3,t}\right) \\
& + \sum_t B_{hp,t}\left(R_{hp,s,t}, S_{s,t,} T_{hp,t}, D_{hp,t}, E_{hp,t}\right) \\
& + \sum_s \sum_t B_{ins,s,t}\left(R_{ins,s,t}, T_{ins,s,t}, D_{ins,s,t}, E_{ins,s,t}\right) \\
& + \sum_s \sum_t B_{rec,s,t}\left(S_{s,t}, T_{rec,s,t}, D_{rec,s,t}, E_{rec,s,t}\right) \\
& - \sum_s C\left(K_s\right)
\end{aligned}$$

Subject to

(i) Mass balance for three reservoirs

$S_{s,t+1} = S_{s,t} + I_{s,t} + P_{s,t} - EV_{s,t} - R_{s,t}$ for s = 1,2 and t = 1,2,…,N

$S_{3,t+1} = S_{3,t} + I_{3,t} + P_{3,t} - EV_{3,t} + R_{1,t} + R_{2,t} - R_{3,t}$ for t = 1,2,…,N

$R_{ins,s,t} = R_{s,t}$ for s=1,2 and for all t.

$R_{ins,3,t} = R_{3,t} - R_{ws,3,t} - R_{irr,3,t}$ for all t.

$R_{hp,s,t} = R_{s,t}$ for s=1,2,3 and for all t.

(ii) Hydropower generation

$\sum_s \xi_s \; R_{s,t} \; h_{s,t}(K_{d,s} + S_{s,t} , K_{d,s} + S_{s,t+1}) + D_{hp,t} - E_{hp,t} = T_{hp,t}$ for all t.

(iii) Target allocation for irrigation

$R_{irr,3,t} + D_{irr,t} - E_{irr,t} = T_{irr,t}$ for all t.

(iv) Target allocation for water supply release

$R_{ws,3,t} + D_{ws,t} - E_{ws,t} = T_{ws,t}$ for all t.

(v) Target allocation for instream flow release in each stream section

$R_{s,t} + D_{ins,s,t} - E_{ins,s,t} = T_{ins,s,t}$ for s=1,2 and for all t.

$R_{3,t} - R_{ws,3,t} - R_{irr,3,t} + D_{ins,3,t} - E_{ins,3,t} = T_{ins,3,t}$ for all t.

(vi) Target allocation for recreation

$K_{d,s} + S_{s,t} + D_{rec,s,t} - E_{rec,s,t} = T_{rec,s,t}$ for s=1,2,3 and for all t.

(vii) Reservoir capacity

$S_{s,t} \leq K_s - K_{d,s}$ for s=1,2,3 and for all t.

(iii) Operation of multi-objective multipurpose reservoir

In cases where operation objectives have trade-offs, single-objective optimization cannot provide a unique optimum solution. Some objectives can be improved by sacrificing the others. Here the concept of "non-inferiority" as explained in the previous lecture replaces the single-objective optimization problem (either maximization or minimization). The most suitable solution is chosen by the operator according to the preferences. In general, a multi-objective reservoir operation problem can be formulated as follows

$$\text{Maximize } Z(X) = [Z_1(X), Z_2(X), \ldots, Z_n(X)]$$

Subject to

$$g_i(X) \geq 0 \text{ for } i = 1, 2, \ldots, m.$$

where X is a vector of decision variables; $Z_j(X)$, $j=1,\ldots, n$ are the objective functions and $g_i(X)$), $i=1,\ldots,m$ are the constraints that define the feasible solutions.