II.4-SSARRESV  SSARR RESERVOIR REGULATION OPERATION

Introduction

This Chapter describes the SSARR reservoir regulation method (Operation SSARRESV) which is based on the Streamflow Simulation and Reservoir Regulation System (SSARR) developed by the North West River Forecast Center and the North Pacific Division of the US Army Corps of Engineers.

The method routes streamflows from upstream to downstream points through lake storage and reservoirs under free flow or controlled-flow modes of operation. Flows may be routed as a function of multivariable relationships involving backwater effects from a downstream reservoir.

The reservoir regulation options are:

- **FREEFLOW** - free flow (lake routing)
- **SETQ** - outflow specified (CFS; CMS)
- **SETH** - reservoir elevation specified (FT; M)
- **SETS** - reservoir storage specified (ACFT; TCUM)
- **SETDQ** - change in storage specified (CFSD/DAY; CMSD/DAY)
- **SETDH** - daily change of elevation specified (FT/DAY; M/DAY)
- **SETDS** - daily change of storage specified (ACFT/DAY; TCUM/DAY)

All the units follow the NWSRFS units convention except TCUM which stands for thousand cubic meters.

The regulation options can change over time and are not specified as part of a Segment definition but are specified at run-time using the SSARREG MOD (see Section VI.5.3C-FCEXC-MOD-SSARREG) as a sequence of regulation options, dates and values. The method used to compute outflow changes between the observed and forecast periods. The specified regulation options are only used to determine the outflow and elevation during the forecast period. During the observed portion of a SSARRESV run, observations are used to determine the outflow and elevation based on the procedures.

When reservoir operations are specified in terms of storage change (SETH, SETS, SETDQ, SETDH, SETDS) the reservoir outflow is being calculated as being parallel to the inflow hydrograph and separated by the stipulated volume amount. When the storage change differs from one period to the next, an instantaneous change in flow must necessarily be utilized. Such a condition is illustrated in Figure 1. Since an instantaneous flow change can occur, Operation SSARRESV requires two instantaneous outflow time series: the first contains the flow at the start of a time period and the second contains the flow at the end of the period. Optionally, a mean outflow time series can be generated (average of flows at the start and end of the period).

Inflow to Operation SSARRESV can be a single inflow time series or a pair of inflow time series (start and end of period flows) depending on which other Operations are used to generate the inflow (see Chapter II.4-SUMPOINT). The typical data type code to use for start of period inflow is:
The general reservoir regulation rules for a computational interval starting at time \( t_i \) and bracketed by regulation options specified at times \( T_i \) and \( T_{i+1} \) are as follows:

1. If no regulation option is specified then:
   - If the outflow/elevation curve is available then FREEFLOW is used.
   - If the outflow/elevation curve is not available then inflow will be passed.

2. If the regulation options at \( T_i \) and \( T_{i+1} \) are the same then the regulation value is linearly interpolated between the values specified at \( T_i \) and \( T_{i+1} \).

3. If the regulation options at \( T_i \) and \( T_{i+1} \) are different then:
   - If the specified option at \( T_{i+1} \) is SETH or SETS then the regulation option at \( T_{i+1} \) is used and the regulation value is linearly interpolated using the computed value from \( t_i \) and the specified value at \( T_{i+1} \).
   - If the specified option at \( T_{i+1} \) is neither SETH nor SETS then FREEFLOW is used.

Operation SSARRESV is normally used for a single reservoir without backwater effect but it can also be used for a single reservoir with backwater effect from tributary flow. A reservoir without backwater effect is referred to as a non-backwater reservoir and a reservoir with backwater effect is referred to as a backwater reservoir. A maximum of two reservoirs, where the outflow from the upstream reservoir is affected by backwater from the downstream reservoir, are permitted in Operation SSARRESV. If there are a pair of reservoirs then both reservoirs are included in a single SSARRESV Operation. The upstream reservoir is always referred to as the backwater reservoir. The downstream reservoir can be a non-backwater reservoir or a backwater reservoir. If the downstream reservoir is a backwater reservoir then only the backwater effect from tributary flow is allowed in Operation SSARRESV.

Operation SSARRESV can also be used to simulate a station in the river with backwater effect from a downstream reservoir. A station with backwater effect is referred to as a backwater station. A backwater station must always be used together with a downstream reservoir and included in a single SSARRESV Operation.

Freeflow Lake Routing

The FREEFLOW lake routing method is used to route floods through a natural lake or a reservoir under free flow condition.
Input parameters needed in lake routing are as follows:
\[ S = F(H) \text{ or } H = F(S) - \text{elevation/storage curve} \]
\[ Q = G(H) \text{ or } Q = G(S) - \text{outflow/elevation/storage curve} \]
\[ H_{\text{MIN}} - \text{minimum pool elevation allowed} \]

The routing of flow through natural lakes is based on free-flow conditions, i.e., elevation-outflow relationships are fixed and outflow is determined by hydraulic head. The basic routing method relies on the law of continuity in the storage equation:
\[ Q_{2} = F(S_{2}) \]

and the outflow/storage curve:
\[ Q = F(S) \]

The two unknowns \( S_{2} \) and \( Q_{2} \) can be solved from the two equations by an iterative procedure depicted in Figure 2. The initial estimate for outflow \( Q_{i} \) is assumed to equal the outflow at period start \( Q_{1} \). An outflow value \( Q_{i} \) is then determined by solution of the continuity equation and the storage equation, according to the elevation-storage relationships that are entered in table form. The \( Q_{i} \) value is then tested and the process repeated until an acceptable outflow is obtained. This iterative process insures an accurate solution of lake routing.

Once the reservoir storage is computed the reservoir elevation can be interpolated from the elevation/storage curve:
\[ H_{2} = F(S_{2}) \]

If \( H_{2} \) is less than \( H_{\text{MIN}} \), \( H_{2} \) is reset to \( H_{\text{MIN}} \) and a new outflow, \( Q_{2} \) is computed to bring the elevation to \( H_{\text{MIN}} \):
\[ H_{2} = H_{\text{MIN}} \]
\[ S_{2} = F(H_{2}) \]
\[ dQ = (S_{1} - S_{2})/dt \]
\[ Q_{2} = I_{2} + dQ \]

and
\[ Q_{1n} = I_{1} + dQ \]

If no outflow/elevation curve is given then inflow is passed thus:
\[ Q_{2} = I_{2} \]
and
\[ Q_{i0} = I_1 \]
and
\[ H_2 = H_1 \]
and
\[ S_2 = S_1 \]

Reservoir Without Backwater Effect

The method described herein is used to route floods through a single reservoir or through the downstream reservoir of a two-reservoir system. In either case the reservoir is assumed to have no backwater effects.

Input parameters needed in a reservoir without backwater effect include the parameters described in lake routing plus HMAX:

- **HMAX** - Maximum pool elevation allowed. If inflow is less than hydraulic capacity, this elevation will be maintained by passing inflow. If inflow exceeds hydraulic capacity then FREEFLOW will be used.
- **QMIN** - Minimum reservoir release for fishery or other water use for as long as the reservoir elevation is above HMIN.

There are six different ways available in Operation SSARRESV to regulate a reservoir.

1. **SETQ - Outflow Specified**

- **Time** = \( T_i, T_{i+1} \)
- **Regulation option** = IX  1
- **Outflow** = \( X \) \( Q_{i+1} \)

where IX is the reservoir regulation option

X is the regulation value associated with the regulation option IX

IX may be any reservoir regulation options from 0 to 6 and X may be outflow, pool elevation, pool storage, delta outflow, delta elevation or delta storage depending on the regulation option IX.

If IX ≠ 1 then the regulation option is changed. The option at \( T_{i+1} \) is different from the option at \( T_i \). \( H_i, Q_i \) and \( S_i \) are solved using the FREEFLOW mode.

If IX = 1 then the same options are used at \( T_i \) and \( T_{i+1} \). Therefore, X = \( Q_i \) and the specified outflow, \( Q_2 \), is computed by linear interpolation from the following equation:
Once the specified outflow, \( Q_2 \) is known, \( S_2 \) is computed from the continuity equation:

\[
S_2 = S_1 + \left[ \frac{I_1 + I_2}{2} \right] \cdot \Delta t - \left[ \frac{Q_1 + Q_2}{2} \right] \cdot \Delta t
\]

Then compute the pool elevation from the elevation/storage curve:

\[
H_2 = F(S_2)
\]

If \( H_2 > H_{\text{MAX}} \) then set \( H_2 = H_{\text{MAX}} \) or if \( H_2 < H_{\text{MIN}} \) then set \( H_2 \) to \( H_{\text{MIN}} \). If \( H_2 \) is revised then recompute \( S_2 \) from \( S_2 = F(H_2) \) and then \( Q_2 \) and \( Q_{\text{in}} \) as follows:

\[
dQ = (S_1 - S_2)/\Delta t
\]

\[
Q_2 = I_2 + dQ
\]

and

\[
Q_{\text{in}} = I_1 + dQ
\]

If \( H_2 > H_{\text{MIN}} \) and \( Q_2 < Q_{\text{MIN}} \) then set \( Q_2 \) to \( Q_{\text{MIN}} \); and recompute \( H_2 \) and \( S_2 \).

The hydraulic capacity corresponding to the reservoir elevation \( H_2 \) is interpolated from the outflow/elevation curve:

\[
Q_C = F(H_2)
\]

If \( Q_2 > Q_C \), recompute \( H_2 \), \( Q_2 \) and \( S_2 \) from the FREEFLOW mode.

2. SETH - Pool Elevation Specified

\[
\text{Time} = T_i, \ T_{i+1}
\]

Regulation option = IX, 2

Elevation = X, \( H_{i+1} \)

where IX is the reservoir regulation option

X is the regulation value associated with the regulation option IX

IX may be any reservoir regulation options from 0 to 6 and X may be outflow, pool elevation, pool storage, delta outflow, delta elevation or delta storage depending on the regulation option IX.

If IX # 2 then the regulation option is changed. The option at \( T_{i+1} \) is different from the option at \( T_i \). The pool elevation, \( H_i \), is computed by linear interpolation using the computed elevation at \( t_i \)
and the specified elevation at $T_{i+1}$.

$$H_2 = H_1 + \left[ \frac{H_{i+1} - H_1}{T_{i+1} - T_1} \right] \ast (t_2 - t_1)$$

If $IX = 2$ then the same options are used at $T_1$ and $T_{i+1}$. Therefore, $X = H_1$ and $H_2$ is computed by linear interpolation from the following equation:

$$H_2 = H_1 + \left[ \frac{H_{i+1} - H_1}{T_{i+1} - T_1} \right] \ast (t_2 - T_1)$$

If $H_2 > H_{\text{MAX}}$ then set $H_2 = H_{\text{MAX}}$. If $H_2 < H_{\text{MIN}}$ then set $H_2 = H_{\text{MIN}}$.

Once $H_2$ is determined, $S_2$ is interpolated from the elevation-storage curve:

$$S_2 = F(H_2)$$

then

$$dQ = (S_1 - S_2)/dt$$

and

$$Q_2 = I_2 + dQ$$

and

$$Q_{1,2} = I_1 + dQ$$

If $H_2 > H_{\text{MIN}}$ and $Q_2 < Q_{\text{MIN}}$ then set $Q_2$ to $Q_{\text{MIN}}$; and recompute $H_2$ and $S_2$ according to the procedures given in the SETQ section.

The hydraulic capacity corresponding to the reservoir elevation $H_2$ is interpolated from the outflow/elevation curve:

$$QC = F(H_2)$$

If $Q_2 > QC$, recompute $H_2$, $Q_2$ and $S_2$ from the FREEFLOW mode.

3. SETS - Pool Storage Specified

Time = $T_1$, $T_{i+1}$
Regulation option = IX 3
Storage = $X$, $S_{i+1}$

where IX is the reservoir regulation option
$X$ is the regulation value associated with the regulation option IX

IX may be any reservoir regulation options from 0 to 6 and $X$ may be
outflow, pool elevation, pool storage, delta outflow, delta elevation or delta storage depending on the regulation option IX.

If IX ≠ 3 then the regulation option is changed. The option at $T_{i+1}$ is different from the option at $T_i$. The reservoir storage, $S_2$, is computed by linear interpolation using the computed storage at $t_i$ and the specified storage at $T_{i+1}$:

$$S_2 = S_1 + \frac{S_{i+1} - S_i}{T_{i+1} - t_i} \times (t_2 - t_1)$$

If IX = 3 then same options are used at $T_i$ and $T_{i+1}$. Therefore $X = S_i$ and $S_2$ is computed by linear interpolation from the following equation:

$$S_2 = S_1 + \frac{S_{i+1} - S_i}{T_{i+1} - T_i} \times (t_2 - T_i)$$

To solve for the rest of the unknowns $H_2$ must be computed from the elevation/storage curve:

$$H_2 = f(S_2)$$

If $H_2 > H_{\text{MAX}}$ then set $H_2 = H_{\text{MAX}}$ or if $H_2 < H_{\text{MIN}}$ then set $H_2$ to $H_{\text{MIN}}$. If $H_2$ is revised then $S_2 = f(H_2)$ is recomputed and:

$$dQ = (S_1 - S_2)/dt$$

$$Q_2 = I_2 + dQ$$

and

$$Q_{1n} = I_1 + dQ$$

If $H_2 > H_{\text{MIN}}$ and $Q_2 < Q_{\text{MIN}}$ then set $Q_2$ to $Q_{\text{MIN}}$; and recompute $H_2$ and $S_2$ according to the procedures given in the SETQ section.

The hydraulic capacity corresponding to the reservoir elevation $H_2$ is interpolated from the outflow/elevation curve:

$$QC = f(H_2)$$

If $Q_2 > QC$, recompute $H_2$, $Q_2$ and $S_2$ from the FREEFLOW mode.

4. SETDQ - Delta Outflow Specified

Time = $T_i$ $T_{i+1}$
Regulation option = IX 4
Delta outflow = $X$ $dQ_{i+1}$

where IX is the reservoir regulation option
$X$ is the regulation value associated with the regulation option IX
IX may be any reservoir regulation options from 0 to 6 and X may be outflow, pool elevation, pool storage, delta outflow, delta elevation or delta storage depending on the regulation option IX.

If IX ≠ 4 then the regulation option is changed. The option at T_i+1 is different from the option at T_i. H_i, Q_i and S_i are solved using the FREEFLOW mode.

If IX = 4 then the same options are used at T_i and T_{i+1}. Therefore, X = dQ, and the outflow change in one period, dQ, is computed by linear interpolation from the following equation:

\[ dQ = dQ_i + \left( \frac{dQ_{i+1} - dQ_i}{T_{i+1} - T_i} \right) \times (t_2 - T_1) \]

The solution procedure to follow is first to compute S_i from:

\[ S_i = S_i + dQ \times dt \]

Then compute H_i from the elevation/storage curve:

\[ H_i = f(S_i) \]

If \( H_i > H_{\text{MAX}} \) then set \( H_i = H_{\text{MAX}} \) or if \( H_i < H_{\text{MIN}} \), reset \( H_i = H_{\text{MIN}} \). If \( H_i \) is revised \( S_i \) and \( dQ \) are recomputed as follows:

\[ S_i = F(H_i). \]

otherwise
\[ dQ = (S_i - S_i)/dt \]
\[ Q_i = I_i + dQ \]

and
\[ Q_{\text{MIN}} = I_i + dQ \]

If \( H_2 > H_{\text{MIN}} \) and \( Q_i < Q_{\text{MIN}} \) then set \( Q_i \) to \( Q_{\text{MIN}} \); and recompute \( H_i \) and \( S_i \) according to the procedures given in the SETQ section.

The hydraulic capacity corresponding to the reservoir elevation \( H_i \) is interpolated from the outflow/elevation curve:

\[ QC = F(H_i) \]

If \( Q_i > QC \), recompute \( H_i, Q_i \) and \( S_i \) from the FREEFLOW mode.

5. SETDH - Daily Change of Elevation Specified

Time = T_i T_{i+1}
Regulation option = X 5
Daily change of Elevation = X dH_{i+1}
where IX is the reservoir regulation option
    X is the regulation value associated with the regulation option IX

IX may be any reservoir regulation options from 0 to 6 and X may be
outflow, pool elevation, pool storage, delta outflow, delta
elevation or delta storage depending on the regulation option IX.

If IX ≠ 5 then the regulation option is changed. The option at Ti+1
is different from the option at Ti. H2, Q2 and S2 are solved using
the FREEFLOW mode.

If IX = 5 then the same options are used at Ti and Ti+1. Therefore X
= dH and the elevation change in one period, dH, is computed by
linear interpolation from the following equation (the change of
elevation is specified on a daily basis):

\[ dH = dH_i + \frac{dH_{i+1} - dH_i}{T_{i+1} - T_i} \times (t_2 - T_1) \]

The solution procedure to follow is first to compute H2 from

\[ H_2 = H_i + dH \times (dt/24) \]

If \( H_2 > H_{MAX} \) then set \( H_2 = H_{MAX} \)
If \( H_2 < H_{MIN} \) then set \( H_2 = H_{MIN} \)

Once \( H_2 \) is determined, \( S_2 \) is interpolated from the elevation-storage
curve:

\[ S_2 = F(H_2) \]

then

\[ dQ = (S_1 - S_2)/dt \]

and

\[ Q_2 = I_2 + dQ \]

and

\[ Q_{1n} = I_1 + dQ \]

If \( H2 > H_{MIN} \) and \( Q_2 < Q_{MIN} \) then set \( Q_2 \) to \( Q_{MIN} \); and recompute \( H_2 \) and
\( S_2 \) according to the procedures given in the SETQ section.

The hydraulic capacity corresponding to the reservoir elevation \( H_2 \)
is interpolated from the outflow/elevation curve:

\[ QC = F(H_2) \]

If \( Q_2 > QC \), recompute \( H_2 \), \( Q_2 \) and \( S_2 \) from the FREEFLOW mode.
6. SETDS - Daily Change of Storage Specified

Time \[ T_i \rightarrow T_{i+1} \]
Regulation option \( IX \rightarrow 6 \)
Daily change of Storage \( X \rightarrow dS_{i+1} \)

where \( IX \) is the reservoir regulation option
\( X \) is the regulation value associated with the regulation option \( IX \)

\( IX \) may be any reservoir regulation options from 0 to 6 and \( X \) may be outflow, pool elevation, pool storage, delta outflow, delta elevation or delta storage depending on the regulation option \( IX \).

If \( X \neq 6 \) then the regulation option is changed. The option at \( T_{i+1} \) is different from the option at \( T_i \). \( H_2, Q_2 \) and \( S_2 \) are solved using the FREEFLOW mode.

If \( IX = 6 \) then the same options are used at \( T_i \) and \( T_{i+1} \). Therefore, \( X = dS_i \) and the storage change in one period, \( dS_i \), is computed by linear interpolation from the following equation (the change of storage is specified on a daily basis):

\[
dS = dS_i + \left[ \frac{dS_{i+1} - dS_i}{T_{i+1} - T_i} \right] (t_2 - T_1)
\]

The solution procedure to follow is first to compute \( S_2 \) from:

\[
S_2 = S_1 + dS \times (dt/24)
\]

Then compute \( H_2 \) from the elevation storage curve:

\[
H_2 = f(S_2)
\]

If \( H_2 > H_{MAX} \) then set \( H_2 = H_{MAX} \) or if \( H_2 < H_{MIN} \) then set \( H_2 \) to \( H_{MIN} \).

If \( H_2 \) is revised then \( S_2 = F(H_2) \) is recomputed and:

\[
dQ = (S_1 - S_2)/dt
\]

\[
Q_2 = I_2 + dQ
\]

and

\[
Q_{12} = I_1 + dQ
\]

If \( H_2 > H_{MIN} \) and \( Q_2 < Q_{MIN} \) then set \( Q_2 \) to \( Q_{MIN} \) and recompute \( H_2 \) and \( S_2 \) according to the procedures given in the SETQ section.

The hydraulic capacity corresponding to the reservoir elevation \( H_2 \) is interpolated from the outflow/elevation curve:

\[
QC = F(H_2)
\]

If \( Q_2 > QC \), recompute \( H_2, Q_2 \) and \( S_2 \) from the FREEFLOW mode.
Reservoir with Backwater Effect from Downstream Reservoir

The method described herein is used to route floods through the upstream reservoir of a two-reservoir system in which the upstream reservoir is backwater affected by the downstream reservoir. The upstream reservoir may also include the backwater effect from tributary flow and local flow occurred in between the two reservoirs. The method used for solving the backwater reservoir in a two-reservoir system is presented herein. A backwater reservoir with backwater effect solely from tributary flow will be discussed in the next section.

Input parameters for solving a reservoir with backwater effect from a downstream reservoir are as follows:

- \( S = F(H) \) or \( H = F(S) \) - Elevation/storage curve
- \( Q = B(H, HH) \) - Three variable backwater curve controlled by downstream reservoir elevation, \( HH \)
  - or
- \( Q = B(H, QQ) \) - Three variable backwater curve controlled by downstream reservoir outflow, \( QQ \)
- \( H_{MAX} \) - Maximum pool elevation for the backwater reservoir above which backwater routing will be used
- \( H_{MIN} \) - Minimum pool elevation for the backwater reservoir

The governing equations used for a backwater reservoir problem are similar to a non-backwater reservoir except the three variable backwater curve.

From the continuity condition:

\[
\left[ \frac{I_1 + I_2}{2} \right] \ dt - \left[ \frac{Q_1 + Q_2}{2} \right] \ dt = S_2 - S_1
\]

From the elevation/storage curve:

\( H_2 = F(S_2) \)

From the three variable backwater curve:

\( Q_2 = B(H_2, HH_2) \)
  - or
\( Q_2 = B(H_2, QQ_2) \)
Notice that there are four unknowns, $Q_2$, $S_2$, $H_2$, and $HH_2$ or $(QQ_2)$, in the above three equations. Four unknowns cannot be solved from only three equations. However if $HH_2$ or $QQ_2$ are lagged by one time step then:

\[ Q_2 = B(H_2, HH_2) \]

or

\[ Q_2 = B(H_2, QQ_2) \]

The four unknown variables have been reduced to three, $Q_2$, $H_2$, and $S_2$. The three unknowns can then be solved from the above three equations: the continuity equation, the elevation/storage curve and the backwater curve. The iterative solution technique is similar to a non-backwater reservoir and is given in Figure 2. Due to the lagging of $HH$ or $QQ$, short computational periods should be used to minimize the computational error.

All the reservoir regulation options described in sections for a non-backwater reservoir are also applicable to a backwater reservoir. The only difference is that the hydraulic capacity for a backwater reservoir is computed from the backwater curve:

\[ QC = B(H_2, HH_2) \]

or

\[ QC = B(H_2, QQ_2) \]

The outflow from the upstream reservoir, $Q_2$, is then used as inflow to the downstream reservoir. If the downstream reservoir is a non-backwater reservoir then the solution technique described earlier is used to complete the computational process. If the downstream reservoir is a backwater reservoir then the backwater reservoir is allowed to have backwater effect only from tributary flow. The solution technique will be discussed in the following section.

Any tributary flow and/or local flow, if existed, must be occurred in between the upstream and downstream reservoirs; and they should be added to the outflow from the upstream reservoir, $Q_2$, before they are used as inflow to the downstream reservoir.

**Reservoir with Backwater Effect Solely from Tributary Flow**

The method described herein is used to route floods through a backwater reservoir with backwater effect solely from tributary flow. In Operation SSARRESV a backwater reservoir of this type is allowed to be used only either as a single reservoir or as the downstream reservoir of a two-reservoir/station system.

Input parameters are as follows:

\[ S = F(H) \text{ or } H = F(S) \] - Elevation/storage curve
\[ Q = B(H, QQ) \] - Three variable backwater curve controlled by tributary flow, \( QQ \)

\( H_{\text{MAX}} \) - Maximum pool elevation for the backwater reservoir above which backwater routing will be used

\( H_{\text{MIN}} \) - Minimum pool elevation for the backwater reservoir

The problem associated with a backwater reservoir affected solely by tributary flow is similar to, but easier than, a reservoir problem backwater controlled by a downstream reservoir. The reasons are that only one control parameter, flow, needs to be considered and that the tributary flow, \( QQ \), is assumed to have been computed elsewhere prior to Operation SSARRESV.

From the continuity condition:

\[
\left[ \frac{I_1 + I_2}{2} \right] \cdot dt - \left[ \frac{Q_1 + Q_2}{2} \right] \cdot dt = S_2 - S_1
\]

From the elevation/storage curve:

\[ H_2 = F(S_2) \]

From the three variable backwater curve:

\[ Q_2 = B(H_2, QQ_2) \]

Since the tributary flow time series is assumed to have been computed from another Operation prior to Operation SSARRESV, \( QQ_3 \) is a known variable. The three unknowns, \( Q_2 \), \( S_2 \) and \( H_2 \) can be solved from the three equations: the continuity equation, the elevation/storage curve and the backwater curve. The iterative solution technique is similar to the reservoir Operation with backwater effect from a downstream reservoir.

All the reservoir regulation options described in sections for a non-backwater are also applicable a backwater reservoir. The only difference is that the hydraulic capacity of a backwater reservoir is computed from the backwater curve:

\[ QC = B(H_2, QQ_2) \]

**Station Using Three-Variable Table Lookup Without Backwater Routing**

The three variable table lookup is available both in Operation SSARRESV and Operation LOOKUP3 however their functions are slightly different. In Operation SSARRESV the three variable table and the regulation options from the downstream reservoir are solved simultaneously. In Operation LOOKUP3 the discharge or elevation time series at the downstream control point is determined apriori from...
another Operation. Therefore if the flow from the upstream station could impose significant change to the elevation of the downstream reservoir or if the downstream reservoir is to be regulated to achieve certain desired flow conditions at the upstream station then Operation SSARRESV should be used. If the backwater effect at the backwater station is solely due to tributary flow or if the downstream reservoir will be operated without regarding the flow condition at the upstream station then Operation LOOKUP3 (three-variable table lookup) should be used.

The method described herein is used to route floods through the upstream station of a station-reservoir system in which the upstream station is backwater affected by the downstream reservoir. Similar to a backwater reservoir, a backwater station in the river may include backwater effect from tributary flow and local flow.

The stage-discharge relationships for a backwater station is specified in a three-variable table when no backwater routing is required. Only the three-variable relation curve is needed to solve a backwater station problem:

\[ H = T(HH, Q) \] - Three variable relation curve controlled by downstream reservoir elevation, \( HH \).

or

\[ H = T(QQ, Q) \] - Three variable relation curve controlled by downstream reservoir outflow, \( QQ \).

From the three-variable relation curve:

\[ H_2 = T(HH_1, Q_1) \]

or

\[ H_2 = T(QQ_1, Q_1) \]

\( Q_2 \) is inflow to the station and is computed elsewhere prior to Operation SSARRESV and therefore is assumed to be a known variable. However there are still two unknowns left, \( H_2 \) and \( HH_2 \) or \( QQ_2 \). A problem cannot be solved with two unknown and only one equation.

However \( HH_2 \) or \( QQ_2 \) are lagged by one time step then:

\[ H_2 = T(HH_1, Q_1) \]

or

\[ H_2 = T(QQ_1, Q_1) \]

The two unknown variables have been reduced to one, \( H_2 \). Given \( HH_1 \) or \( QQ_1 \) as first independent variable and \( Q_1 \) as second independent variable, \( H_2 \) can be interpolated through a three-variable table lookup. Due to the lagging of \( HH \) or \( QQ \), short computational periods should be used to minimize the computational error.
In Operation SSARRESV inflow is assume to be equal to outflow at a backwater station. Therefore the flow at the upstream station, \( Q_u \), is then used as inflow to the downstream reservoir. The solution technique for the downstream reservoir, either a backwater or a non-backwater reservoir, is used to complete the computational process.

Any tributary flow and/or local flow, if existed, must be occurred in between the upstream station and the downstream reservoir; and they should be added to the outflow from the upstream station, \( Q_u \), before they are used as inflow to the downstream reservoir.

Method to Generate Results from Observed Data

All the observed data are assumed to have been obtained at the end of a time period. Different generation procedures are used depending on types of available observed data.

Seven cases of different combinations of observed data are possible:

- Case 1. Only observed instantaneous discharge (OQ) is available
- Case 2. Only observed mean discharge (OQM) is available
- Case 3. Only observed pool elevation (OH) is available
- Case 4. Both observed instantaneous and mean discharge are available
- Case 5. Both observed instantaneous discharge and pool elevation are available
- Case 6. Both observed pool elevation and mean discharge are available
- Case 7. All three types of observed data are available

Depending on the combinations of observed data, different procedures need to be utilized to generate the results. The procedures used in each of the seven cases are presented separately as follows:

**Case 1 - Only observed instantaneous discharge is available**

**Step A. Generate instantaneous discharges:**

Since observed data are obtained at period end instantaneous discharge at period end is equal to observed, \( Q_t = OQ \), whenever observed instantaneous discharges are available. If observed instantaneous discharges are missing then the missing discharges are generated from two adjacent non-missing discharges by linear interpolation. The process is repeated throughout the entire time series to generate all the instantaneous discharges at period end.

Once all the instantaneous discharges at period end are determined the instantaneous discharge at period start, \( Q_{is} \), can be computed as follows:

\[
\Delta Q = Q_t - I_t
\]

and
\[ Q_{in} = I_1 + d \]

**Step B. Generate mean discharge from** \( \bar{Q}_M = (Q_1 + Q_{in})/2 \)

**Step C. Generate pool elevations and storages:**

Let \( \bar{I}_M = (I_1 + I_2)/2 \) then compute pool storage, \( S_2 \), from continuity equation using mean discharge, \( \bar{Q}_M \), generated from step B:

\[ S_2 = S_1 + (\bar{I}_M - \bar{Q}_M) \times dt \]

then interpolate pool elevation, \( H_2 \), from elevation/storage curve:

\[ H_2 = F(S_2) \]

**Case 2 - Only observed mean discharge is available**

**Step A. Generate mean discharges:**

Set \( \bar{Q}_M = OQM \), whenever observed mean discharges are available.

If observed mean discharge are missing then the missing mean discharges are generated from two adjacent non-missing mean discharges through linear interpolation.

**Step B. Generate instantaneous discharges:**

First compute the mean inflow, \( \bar{I}_M \), then \( dQ \) using the mean discharge, \( \bar{Q}_M \), generated from step A:

\[ \bar{I}_M = (I_1 + I_2)/2 \]

and

\[ dQ = \bar{Q}_M - \bar{I}_M \]

then

\[ Q_2 = I_2 + dQ \]

and

\[ Q_{in} = I_1 + dQ \]

**Step C. Generate pool elevations and storages:**

First compute pool storage, \( S_2 \), using continuity equation and mean discharge generated from Step A:

\[ S_2 = S_1 + (\bar{I}_M - \bar{Q}_M) \times dt \]

Then interpolate pool elevation, \( H_2 \), from elevation/storage curve:
\[ H_2 = F(S_2) \]

**Case 3 - Only observed pool elevations available**

Step A. Generate pool elevations and storages:
First compute pool storages corresponding to all observed pool elevations from pool elevation/storage curve:
\[ OS = F(OH) \]
Set \( S = OS \), whenever observed pool elevations are available. Whenever observed pool elevations are missing the pool storages are generated from two adjacent non-missing storages through linear interpolation. The interpolated storages then used to compute pool elevation from pool elevation/storage curve:
\[ H_2 = F(S_2) \]

Step B. Generate instantaneous discharges:
First compute \( dQ \) from pool storages, \( S_2 \), determined from step A:
\[ dQ = \frac{(S_1 - S_2)}{dt} \]
then
\[ Q_i = I_2 + dQ \]
and
\[ Q_{i,n} = I_1 + dQ \]

Step C. Generate mean discharge from \( Q_M = (Q_2 + Q_{i,n})/2 \)

**Case 4 - both observed instantaneous and mean discharge are available**

Step A. If observed instantaneous discharges are available at period start and end, compute mean discharge from:
\[ Q_M = (Q_2 + Q_{i,n})/2 \]

Step B. The computed mean discharges from Step A are used to supplement the observed mean discharge time series in dealing with missing data. If observed mean discharge is missing and observed instantaneous discharges at period start and end are available then the missing mean discharge will be replaced by the mean discharge computed from the observed instantaneous discharges. A composite time series that combines observed instantaneous and mean discharges is evolved as a new mean discharge time series.

Step C. Generate missing mean discharges in the composite time series in Step B. The missing mean discharges are generated from two adjacent non-missing mean discharges through linear
interpolation.

Step D. Generate instantaneous discharges using the Step B procedure in Case 2

Step E. Replace all instantaneous discharges with observed instantaneous discharges if they are available.

Step F. Generate pool elevations and storages using the Step C procedure in Case 2

**Case 5 - both observed instantaneous discharge and pool elevation available**

Step A. Assuming only observed pool elevation is available, generate pool elevations, storages and instantaneous discharges using the step A and B procedures in Case 3.

Step B. Replace all instantaneous discharges with observed instantaneous discharges if they are available.

Step C. Generate mean discharge from $\text{QM} = (Q_1 + Q_2)/2$

**Case 6 - both observed mean discharge and pool elevation are available**

Step A. Assuming only observed mean discharge is available, generate mean and instantaneous discharges using the Step A and B procedures in Case 2.

Step B. Generate pool elevations and storages:

First compute pool storages corresponding to all observed pool elevations from elevation/storage curve:

$\text{OS} = F(OH)$

Set pool storage to $\text{OS}$, $S_2 = \text{OS}$, whenever observed pool elevations are available. Whenever observed pool elevations are missing, pool storage is computed from continuity equation:

$S_2 = S_1 + (\text{IM} - \text{QM}) \cdot dt$

Then interpolate pool elevation from elevation/storage curve:

$H_2 = F(S_2)$

**Case 7 - All three types of observed data available**

Step A. Assuming only observed instantaneous and mean discharges are available, generate instantaneous and mean discharges using the procedures given in Case 4.

Step B. Then generate pool elevations and storages using the Step B procedure given in Case 6
Method to Back-compute Inflow from Observed Pool Elevation and Discharge

Depending on the combinations of the observed data, different procedures are used to generate the instantaneous discharges at period start and end, mean discharges and pool elevations. The generated results can then be used to back-compute the inflow at period start and end and mean inflow.

First compute the pool storage from the generated pool elevation from pool elevation/storage curve at period start:

\[ S_1 = F(H_1) \]

and the pool storage at period end:

\[ S_2 = F(H_2) \]

Then compute the mean inflow from the continuity equation:

\[ IM = (S_2 - S_1)/dt + QM \]

Then compute the change in flow to conserve storage volume change from:

\[ dQ = QM - IM \]

Then the inflow at period end as:

\[ I_2 = Q_2 - dQ \]

and the inflow at period start as:

\[ I_{in} = Q_{in} - dQ \]
Table 1. Description of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1, I_2$</td>
<td>Inflows at the time period start and end</td>
</tr>
<tr>
<td>$Q_{1n}$</td>
<td>Revised outflow at the time period start to account for volume change; equals $Q_1$ if no volume change occurred</td>
</tr>
<tr>
<td>$Q_1, Q_2$</td>
<td>Outflows at the time period start and end</td>
</tr>
<tr>
<td>$QQ_1, QQ_2$</td>
<td>Control flows at the time period start and end</td>
</tr>
<tr>
<td>$QC$</td>
<td>Hydraulic capacity, maximum discharge capacity of all discharge facilities</td>
</tr>
<tr>
<td>$H_1, H_2$</td>
<td>Pool elevations at the time period start and end</td>
</tr>
<tr>
<td>$HH_1, HH_2$</td>
<td>Control elevations at the time period start and end</td>
</tr>
<tr>
<td>$S_1, S_2$</td>
<td>Pool storages at the time period start and end</td>
</tr>
<tr>
<td>$t_1, t_2$</td>
<td>Time at the time period start and end</td>
</tr>
<tr>
<td>$dt$</td>
<td>Time duration = $t_2 - t_1$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Beginning time of a pair of consecutive time stamp for regulation option bracketing $t_2$</td>
</tr>
<tr>
<td>$T_{i+1}$</td>
<td>Ending time of a pair of consecutive time stamp for regulation option bracketing $t_2$</td>
</tr>
<tr>
<td>IX</td>
<td>Regulation option corresponding to time stamp $T_i$</td>
</tr>
<tr>
<td>X</td>
<td>Regulation value corresponding to regulation option IX</td>
</tr>
<tr>
<td>$Q_{i}, Q_{i+1}$</td>
<td>Regulation outflows corresponding to $T_i$ and $T_{i+1}$</td>
</tr>
<tr>
<td>$H_{i}, H_{i+1}$</td>
<td>Regulation elevations corresponding to $T_i$ and $T_{i+1}$</td>
</tr>
<tr>
<td>$S_{i}, S_{i+1}$</td>
<td>Regulation storages corresponding to $T_i$ and $T_{i+1}$</td>
</tr>
<tr>
<td>$dQ_{i}, dQ_{i+1}$</td>
<td>Regulation delta-outflows corresponding to $T_i$ and $T_{i+1}$, respectively</td>
</tr>
<tr>
<td>$dH_{i}, dH_{i+1}$</td>
<td>Regulation delta-elevations corresponding to $T_i$ and $T_{i+1}$, respectively</td>
</tr>
<tr>
<td>$dS_{i}, dS_{i+1}$</td>
<td>Regulation delta-storages corresponding to $T_i$ and $T_{i+1}$, respectively</td>
</tr>
</tbody>
</table>
Figure 1. Instantaneous flow change
Figure 2. Lake and backwater routing techniques used in SSARR

\[ \text{ENTER} \]

\[ b = \frac{l_1 + l_2}{2} \]

OTHER COMPUTATIONS

NO

LAKES & BACKWATER?

YES

TEST = 0.001 * Q1

ARE \% ELEV. RELATIONSHIP GIVEN?

YES

FIND: \( Q_2 = \frac{l_1 - Q_1}{b + 1/2} + Q_1 \)

ASSUME: \( Q_2 = Q_1 \)

NO

\[ \Delta S = CF \times \left( \frac{b - Q_1 + Q_2}{2} \right) \]

\[ S_o = S_t + \Delta S \]

FIND: \( E_b = f(S_t) \)

BACKWATER?

YES

FIND: \( Q_t = f(E_b) \)

NO

\[ Q_t = \frac{Q_1 + Q_2}{2} \]

NEXT TRIAL

TRIALS = 20

Q2 CALCULATED

YES

TEST

NO

NEXT ASSUMPTION

\[ Q_2 = \frac{Q_1 + Q_1}{2} \]