Flood Storage Allocation Rules for Parallel Reservoirs

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Oroville reservoir and New Bullards Bar reservoir above Marysville in Sacramento River system

Legend:
- Flow Boundary
- Stage Boundary

Schematic

Oroville Reservoir
Flood Control Capacity: 750 TAF

New Bullards Bar Reservoir
Flood Control Capacity: 170 TAF
Oroville reservoir and New Bullards Bar reservoir above Marysville, 1997 Flood

Historical real-time operation of the 1997 flood for Oroville Reservoir (left) and New Bullards Bar Reservoir (right) (HEC-DSS).
Oroville reservoir and New Bullards Bar reservoir above Marysville, 1997 Flood

1997 Flood operation results

Reservoir flood control capacity

- Oroville 750 TAF
- New Bullards Bar 170 TAF

Flood Storage volume used

- Oroville 659 TAF
- New Bullards Bar 170 TAF

Percentage of total flood storage capacity

- Oroville 80%
- New Bullards Bar 20%
Key factors in flood operation for parallel reservoirs

Flood Hydrograph

- Shape
- Duration of flood
- Peak inflow
- Duration of peak inflow

Reservoir Storage
- Initial Storage
- Flood Control Capacity
- Constraints

Travel Time
- Outflow to junction
- Assuming Peak coincide

Outflow Capacity
- Channel capacity
- Maximum release
- Constraints
Key factors in flood operation for parallel reservoirs -- Hydrograph shape

Same Peak reduction ≠ Same flood storage volume

Why Hydrograph Shape?

- Same peak inflow
- Same incoming flood volume

\[ \Delta Q_1 = \Delta Q_2 \]
Key factors in flood operation for parallel reservoirs

-- Hydrograph shape

Hydrograph

1. Triangular
2. Abrupt wave
3. Flood pulse
4. Broad peak
Distinguish hydrograph -- Flood Storage Efficiency (FSE)

Peak inflow reduction VS. Flood storage volume

Inflow

\[ Q_{in,peak} \]
\[ Q_{out,peak} \]
Base flow

Time

Peak Inflow Reduction

Flood Storage Volume

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Distinguish hydrograph
-- Flood Storage Efficiency (FSE)

**Flood Storage Efficiency**

Definition: peak reduction per unit storage

\[ E_i = \frac{\Delta Q_i}{S_i} \]

Peak inflow reduction VS. Flood storage volume
Distinguish hydrograph
-- Marginal Flood Storage Efficiency (MFSE)

\[ E_i = \frac{\Delta Q_i}{S_i} \]

change of FSE with small additional peak reduction

\[ ME_i = \frac{\partial \Delta Q_i}{\partial S_i} \]

Marginal FSE

\[ \Delta Q \]

Peak Inflow Reduction (Total)

Peak Reduction per unit Storage

FSE

\[ \Delta \Delta Q \]

Flood Storage Volume

\[ \Delta S_i \]

peak reduction per unit storage

\[ \text{Flood Storage Volume} \]
Simple optimal allocation

**Rules:** Same MFSE!

**Objective**
Minimize damage from downstream peak flow

\[ Z = D \sum_{i} Q_{i,\text{outpeak}} \]

**Constraints**
1. Flow conservation
2. Peak outflow reduction
3. Reservoir capacity
4. Total flood storage capacity
5. Non-negative outflow
6. Non-negative flood storage

**Theoretical Results**
Ideally, one would allocate storage to provide the same MFSE for each reservoir in parallel.

\[ MFSE_i = MFSE_j \]
Uncertain flood hydrographs

Rules: Same MFSE!

Objective

Minimize damage from downstream peak flow

\[ Z = \sum_{f=1}^{m} p_f D \sum_{i=1}^{n} Q_{i,\text{outpeak}} \]

- \( p_f \) – probability of each uncertain hydrograph

Constraints

1. Flow conservation
2. Peak outflow reduction
3. Reservoir capacity
4. Total flood storage capacity
5. Non-negative outflow
6. Non-negative flood storage

Theoretical Results

Ideally, one would allocate storage to provide the same MFSE for each reservoir in parallel.

\[ MFSE_i = MFSE_j \]
Optimal operation for Oroville reservoir and New Bullards Bar reservoir based on hydrograph

Approximation of 1997 flood hydrographs

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Base flow (cfs)</th>
<th>Incoming flood volume (TAF)</th>
<th>Peak inflow (cfs)</th>
<th>Rising limb</th>
<th>Recession limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oroville</td>
<td>70000</td>
<td>941.97</td>
<td>302,004</td>
<td>1.78</td>
<td>1.55</td>
</tr>
<tr>
<td>New Bullards Bar</td>
<td>20000</td>
<td>314.44</td>
<td>104.480</td>
<td>0.56</td>
<td>0.81</td>
</tr>
</tbody>
</table>
## Optimal operation for Oroville reservoir and New Bullards Bar reservoir based on hydrograph

<table>
<thead>
<tr>
<th>Historical allocations, Total flood storage capacity = 829 TAF</th>
<th>Oroville</th>
<th>New Bullards Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood storage volume (TAF)</td>
<td>659</td>
<td>170</td>
</tr>
<tr>
<td>Flood storage capacity used (%)</td>
<td>93</td>
<td>100</td>
</tr>
<tr>
<td>Percentage of total flood storage (%)</td>
<td>79</td>
<td>21</td>
</tr>
<tr>
<td>Peak inflow reduction (cfs)</td>
<td>141,087</td>
<td>49,075</td>
</tr>
<tr>
<td>Outflow (cfs)</td>
<td>160,917</td>
<td>55,005</td>
</tr>
<tr>
<td>MFSE</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Downstream Peak flow (cfs)</td>
<td></td>
<td>215,922</td>
</tr>
</tbody>
</table>

**Case (1): Optimized allocations. Total flood storage capacity = 829 TAF. Unchanged reservoir storage capacity**

| Flood storage volume (TAF)                                   | 659      | 170              |
| Flood storage capacity used (%)                              | 93       | 100              |
| Percentage of total flood storage (%)                        | 80       | 20               |
| Peak inflow reduction (cfs)                                  | 187,816* | 55,300*          |
| Outflow (cfs)                                                | 114,188* | 48,780*          |
| MFSE                                                         | 3.76E-06 | 4.60E-06         |
| Downstream Peak flow (cfs)                                   |          | 162,968          |

**Case (2): Optimized allocations. Total flood storage capacity = 600 TAF. Unchanged reservoir storage capacity**

| Flood storage volume (TAF)                                   | 431      | 169              |
| Flood storage capacity used (%)                              | 57       | 99               |
| Percentage of total flood storage (%)                        | 72       | 28               |
| Peak inflow reduction (cfs)                                  | 146,664  | 55,032           |
| Outflow (cfs)                                                | 155,340  | 49,448           |
| MFSE                                                         | 4.62E-06 | 4.62E-06         |
| Downstream Peak flow (cfs)                                   |          | 204,788          |

**Case (3): Optimized allocations. Total flood storage capacity = 829 TAF. New Bullards Bar Reservoir has additional 80 TAF available capacity for flood control**

| Flood storage volume (TAF)                                   | 595      | 234              |
| Flood storage capacity used (%)                              | 79       | 94               |
| Percentage of total flood storage (%)                        | 72       | 28               |
| Peak inflow reduction (cfs)                                  | 177,053  | 67,180           |
| Outflow (cfs)                                                | 124,951  | 36,900           |
| MFSE                                                         | 3.95E-06 | 3.95E-06         |
| Downstream Peak flow (cfs)                                   |          | 161,851          |
Optimal operation for Oroville reservoir and New Bullards Bar reservoir based on hydrograph

Historical and Optimal operation of the 1997 flood for Oroville Reservoir (left) and New Bullards Bar Reservoir (right) (HEC-DSS).
Conclusions and Future works

• Main Conclusions

• Hydrographs represented by flood storage efficiency (FSE) do affect flood storage allocation for parallel reservoirs.
• The ideal unconstrained allocation of total flood storage capacity is for parallel reservoirs to have the same MFSEs.
• The Two-Stage Stochastic Method is the best for uncertain storms.
• Additional increased (reduced) total flood storage will be allocated to reservoir with bigger (smaller) MFSE.

• Future Works

• Peak attenuation and travel time along the stream, unregulated downstream tributary inflow, hydraulic uncertainty could be included.
• Impact from damage function in various forms will be analyzed.
• Combined with the flood operation for reservoirs in series, optimal operation rules can be derived for a multiple reservoirs system.