Stochastic Reservoir Reliability Analysis

Anderson Dam Seismic Retrofit Project

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ADSRP Project Management Team

FMA Annual Conference
Long Beach, Ca 2017

Creating Partnerships through Integration: Water, Environment, People
Anderson Dam

Stochastic Reservoir Reliability Analysis
Anderson Dam

Stochastic Reservoir Reliability Analysis

Seismic environment

1911 Calaveras (6.5)

1984 Morgan Hill (6.1)

1979 Coyote Lake (5.7)

1989 Loma Prieta (6.9)
Anderson Dam Seismic Retrofit Project

- Remnant dam clay core to remain
- Post Project dam footprint
- Existing dam footprint
- Existing dam clay core

Stochastic Reservoir Reliability Analysis
Anderson Dam Seismic Retrofit Project

Stochastic Reservoir Reliability Analysis

Anderson Dam Generalized Cross-Section (NAVD88)

Max Water Surface, EL 628 ft
10% of Storage, EL 608 ft
90% of Storage
EL 462.5 ft

EL 578.2 ft
HLOW

EL 576 ft – into spillway channel

Dam Crest, EL 656 ft

EL 412.5 ft

Ground Surface

Low-Level Outlet Works (LLOW)
- 6-foot diameter
- 1275 cfs capacity

High-Level Outlet Works (HLOW)
- 12-ft diameter
- 2000-4000 cfs capacity
**Project Construction Sequence**

**How reliable is this?**

- **Year 1:** Dewatering, Outlet Tunnel Construction
- **Dry Season**: Lower Dam to Interim Height (El 570 ft)
- **Interim EL (570 ft) Winter 1**
- **Dry Season**: Lower Dam to remnant core; re-build to Interim Height (El 570 ft)
- **Interim EL (570 ft) Winter 2**
- **Dry Season**: Build Dam to Full Elevation (El 656 ft)
- **Complete Construction (El 656 ft)**

* * Dry Season = April to October
Diversion Operation Plan

Stochastic Reservoir Reliability Analysis

► No operating spillway during construction

► Reduced interim dam height over winter
  ► Reduced storage capacity
  ► Higher overtopping risk
  ► Higher risk of downstream flood impacts

► Primary Objective: Maintain confidence in dam operation to prevent overtopping the interim dam.

► Secondary Objective: Minimize flood risk downstream, subject to primary objective of preventing overtopping.
Why a Stochastic Analysis?

Stochastic Reservoir Reliability Analysis

[Graph showing reservoir elevation over time with a marked increase and peak]
Stochastic Approach

Stochastic Reservoir Reliability Analysis

Synthetic Rainfall Generation

Calibrated Runoff Routing

Reservoir Routing & Reliability
Stochastic Approach

Stochastic Reservoir Reliability Analysis

“THIS IS YOUR MACHINE LEARNING SYSTEM?”

“YUP! YOU POUR THE DATA INTO THIS BIG PILE OF LINEAR ALGEBRA, THEN COLLECT THE ANSWERS ON THE OTHER SIDE.”

“What if the answers are wrong?”

“JUST STIR THE PILE UNTIL THEY START LOOKING RIGHT.”

“I have a master’s degree.....in science!”
Precipitation Data

Stochastic Reservoir Reliability Analysis

[Map showing precipitation data with various stations and drainage areas marked.]
At Mount Hamilton gage, M.A.P of 30-year subset is within 0.5% of M.A.P. of 108-year record.
Statistical Distributions of Historical Data

Stochastic Reservoir Reliability Analysis

► November Dry Period Durations (Lognormal or GEV)

Density plot

PARANORMAL DISTRIBUTION
November Wet Period Durations (GEV)
Statistical Distributions of Historical Data

Stochastic Reservoir Reliability Analysis

► November Wet Period Depths (3 hour)
Modeling Persistence Evident in the Data

Stochastic Reservoir Reliability Analysis

► Challenge: Applying statistical distributions to create a realistic time series.

► Solution: Markov Chain Monte Carlo
Modeling Persistence Evident in the Data

Stochastic Reservoir Reliability Analysis

\[
\begin{align*}
&[[0.1,0.1,0.1,0.1,0.1,0.1,0.3,0.2], \\
&[0.1,0.3,0.2,0,0,0.2,0,0.2], \\
&[0,0.1,0.2,0,0.2,0,0,0.5], \\
&[0.2,0.1,0.1,0,0.1,0.1,0.3,0.1], \\
&[0.2,0.3,0,0.2,0,0.2,0,0.1], \\
&[0.1,0.1,0.2,0,0.2,0,0.1,0.3], \\
&[0,0.1,0.1,0.1,0.3,0.2,0,0.2], \\
&[[0,0.1,0.2,0,0.1,0.1,0.1,0]]
\end{align*}
\]
## Modeling Persistence Evident in the Data

### Transition Probability to Dry Duration

<table>
<thead>
<tr>
<th>Wet Duration</th>
<th>1 hr</th>
<th>2 hr</th>
<th>3-5 hr</th>
<th>Etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hr</td>
<td>$P_{11}$</td>
<td>$P_{12}$</td>
<td>$P_{13}$</td>
<td>...</td>
</tr>
<tr>
<td>2 hr</td>
<td>$P_{21}$</td>
<td>$P_{22}$</td>
<td>$P_{23}$</td>
<td>...</td>
</tr>
<tr>
<td>3-5 hr</td>
<td>$P_{31}$</td>
<td>$P_{32}$</td>
<td>$P_{33}$</td>
<td>...</td>
</tr>
<tr>
<td>6-11 hr</td>
<td>$P_{41}$</td>
<td>$P_{42}$</td>
<td>$P_{43}$</td>
<td>...</td>
</tr>
<tr>
<td>&gt; 12 hr</td>
<td>$P_{51}$</td>
<td>$P_{52}$</td>
<td>$P_{53}$</td>
<td>...</td>
</tr>
</tbody>
</table>
Modeling Persistence Evident in the Data

Stochastic Reservoir Reliability Analysis

Monthly Transition Prob. Distribution

<table>
<thead>
<tr>
<th>Wet Duration</th>
<th>Jan</th>
<th>Feb</th>
<th>Etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Current&quot; Wet Duration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"Next" Dry Duration

Density plots for wet duration transitions:
- January
- February
- March...

Density plots for dry duration transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Density plots for etcetera transitions:
- January
- February
- March...

Modeling Persistence Evident in the Data

Stochastic Reservoir Reliability Analysis

► Next, a pattern is applied, but where does the pattern come from?

1. Sample *Dry*
2. Sample *Wet*
3. Apply Realistic Distribution
Creating Realistic Hourly Precipitation Patterns

▶ Historical Patterns are stored (limited # of possibilities)

▶ A Markov approach also applied to creating additional patterns and build a “library”
For each hour of a given duration:

<table>
<thead>
<tr>
<th>Preceding % of Event</th>
<th>0-0.1</th>
<th>0.1-0.2</th>
<th>0.2-0.3</th>
<th>Etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.1</td>
<td>$P_{11}$</td>
<td>$P_{12}$</td>
<td>$P_{13}$</td>
<td>...</td>
</tr>
<tr>
<td>0.1 - 0.2</td>
<td>$P_{21}$</td>
<td>$P_{22}$</td>
<td>$P_{23}$</td>
<td>...</td>
</tr>
<tr>
<td>0.2 - 0.3</td>
<td>$P_{31}$</td>
<td>$P_{32}$</td>
<td>$P_{33}$</td>
<td>...</td>
</tr>
<tr>
<td>0.3 - 0.4</td>
<td>$P_{41}$</td>
<td>$P_{42}$</td>
<td>$P_{43}$</td>
<td>...</td>
</tr>
<tr>
<td>Etc.</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Creating Realistic Hourly Precipitation Patterns

Transition Prob. Distribution Each Hr

<table>
<thead>
<tr>
<th>Preceding % of Event</th>
<th>Hour 2</th>
<th>Hour 3</th>
<th>Etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 - 0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Synthetic Trace

Stochastic Reservoir Reliability Analysis

Dry Duration → Wet Duration → Event Depth → “Random” Pattern → Repeat

\[ T_D \quad T_W \quad D_T \]

\[
\begin{bmatrix}
X_1 \\
X_2 \\
\vdots
\end{bmatrix}
\]
Dry Duration → Wet Duration → Event Depth → “Random” Pattern → Repeat

\[ [0 \ 0 \ ... \ T_D = 0] \quad D_T \ast [X_1 \ X_2 \ ... \ X_T] \]

Histogram of Hourly Rainfall Depth (in)

Hourly Rainfall Depth (in)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

Hour

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
12,000 “years” of hourly synthetic traces
Annual Precipitation Depth

Time (yrs)

Precipitation Depth (in)

0 10 20 30 40 50 60 70

0 2000 4000 6000 8000 10000 12000
Preservation of Historical Statistics

Stochastic Reservoir Reliability Analysis

Henry Coe Park Rainfall

Gage Mean Annual Precipitation = 27.4 inches
Generated Mean Annual Precipitation = 27.8 inches
Preservation of Historical Statistics

Stochastic Reservoir Reliability Analysis

Henry Coe Park Monthly Rainfall

- Coe Gage Standard Deviation
- Generated Record Standard Dev

- September
- October
- November
- December
- January
- February
- March
- April
- May
- June
- July
- August
Probable Maximum Precipitation

- Reductions for “statistically possible” events that may not be physically possible

- Based on NOAA/NWS Hydrometeorological Report 59 for California
Continuous Hydrologic Modeling

Stochastic Reservoir Reliability Analysis

► Simple Catchment Model: SCS Curve Number & Unit
Hydrograph Convolution

\[ Q = \frac{(P - I_a)^2}{(P - I_a) + S} \]

\[ I_a = 0.2S \]

\[ S = \frac{100}{CN} - 10 \]

P = precipitation (from synthetic trace)
CN = Curve Number (watershed parameter)
Continuous Hydrologic Modeling

Stochastic Reservoir Reliability Analysis

► Antecedent Moisture Condition (AMC)
  ► significant impact to Curve Number
  ► continuously modeled as look-back function based on total 5-day antecedent rainfall

<table>
<thead>
<tr>
<th>AMC</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&lt; 0.5 inch</td>
<td>&lt; 1.4 inches</td>
</tr>
<tr>
<td>II</td>
<td>0.5 inch – 1.1 inches</td>
<td>1.4 – 2.1 inches</td>
</tr>
<tr>
<td>III</td>
<td>&gt; 1.1 inches</td>
<td>&gt; 2.1 inches</td>
</tr>
</tbody>
</table>

► Calibrate lag for each basin
  ► Coyote Reservoir: 8.0 hours
  ► Anderson Reservoir: 5.7 hours

Continuous Hydrologic Modeling

Stochastic Reservoir Reliability Analysis

Gaged Coyote Flow

Modeled Coyote Runoff
Reservoir Routing

Stochastic Reservoir Reliability Analysis

► Route through Coyote Reservoir

Coyote Reservoir

Discharge (cfs)

Storage (AF)

Elevation (ft NAVD)

Storage
Outlet Discharge
Spillway Discharge
Reservoir Routing

Dam Overtopping Reliability Analysis

- Coyote Reservoir outflow hydrograph is routed to Anderson Reservoir using a convex stream routing function.

\[ O_{t+dt} = (1 - C)O_t + CI_t \]

\[ C = \frac{dt}{\text{travel time}} \]

- A one-hour time step is used in all simulations.
Reservoir Routing

Stochastic Reservoir Reliability Analysis

Route through Anderson Reservoir (Existing Outlet)

Anderson Reservoir (Existing)

Discharge (cfs)

Storage (AF)

Elevation (ft NAVD)

Storage
Outlet Discharge
Spillway Discharge
Route through Anderson Reservoir (Fully Open LLOT)

Anderson Reservoir (Project)

- Discharge (cfs)
- Elevation (ft NAVD)
- Storage (AF)

Storage
- Interim Dam Height
- Fully Open Diversion Discharge
Interim Reservoir Elevation and Outflow

Anderson Elevation and Outflow

Elevation (ft NAVD)

Outflow (cfs)

Time
Peak Anderson Elevations w/ Interim Dam and LLOT

Dam Overtopping Reliability Analysis

- Route with PMP adjustment (Fully Open LLOT)
**Model Sensitivity & Stability**

Stochastic Reservoir Reliability Analysis

► **Have we rinsed and repeated enough times?**

(666 simulations per hour of computing time)

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**Elevation 570 Exceedance**

![Graph showing Elevation 570 Exceedance]

**Elevation 560 Exceedance**

![Graph showing Elevation 560 Exceedance]
Downstream Release

Stochastic Reservoir Reliability Analysis

► Frequency of downstream release

![Graph showing the frequency of downstream release. The x-axis represents Total Discharge (cfs), and the y-axis represents Annual Exceedance Probability. The graph includes two lines: red for FEMA Operation and blue for Diversion (Fully Open).]
Conclusions and Ongoing Work

Stochastic Reservoir Reliability Analysis

► Without outlet valve operation, interim reservoir reliability is 99.97 percent

► Working with DSOD, FERC and SCVWD
  ► Interim dam reliability with 10 feet of freeboard
  ► Reduce downstream flooding based on established thresholds, subject to overtopping risk

► Modulate the valve to accomplish both objectives

► Interim Operating Rule Curve
Questions?

Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS
### Impact of Interim Dam Height on Reliability

**Stochastic Reservoir Reliability Analysis**

<table>
<thead>
<tr>
<th>Elevation (ft NAVD)</th>
<th>Failure per 12,000</th>
<th>AEP (%)</th>
<th>Reliability</th>
<th>Risk of Failure 2 Winters (%)</th>
<th>Risk of Failure 3 Winters (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>520</td>
<td>21</td>
<td>0.17</td>
<td>99.83</td>
<td>0.35</td>
<td>0.52</td>
</tr>
<tr>
<td>530</td>
<td>13</td>
<td>0.011</td>
<td>99.89</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>540</td>
<td>5</td>
<td>0.04</td>
<td>99.96</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>543</td>
<td>3</td>
<td>0.03</td>
<td>99.97</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>550</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>570</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>572</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>600</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>630</td>
<td>1</td>
<td>0.01</td>
<td>99.99</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>636</td>
<td>0</td>
<td>n/a</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
## Interim Dam at 570 feet NAVD and LLOT Fully Open

<table>
<thead>
<tr>
<th>Maximum Release (cfs)</th>
<th>Occurrence per 12,000 simulations</th>
<th>AEP (%)</th>
<th>Risk of Release 2 Winters (%)</th>
<th>Risk of Release 3 Winters (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>9,188</td>
<td>76.6</td>
<td>91.7</td>
<td>97.6</td>
</tr>
<tr>
<td>2,000</td>
<td>7,746</td>
<td>64.6</td>
<td>87.4</td>
<td>95.6</td>
</tr>
<tr>
<td>3,000</td>
<td>1,504</td>
<td>12.5</td>
<td>23.5</td>
<td>33.1</td>
</tr>
<tr>
<td>4,000</td>
<td>37</td>
<td>0.31</td>
<td>0.62</td>
<td>0.92</td>
</tr>
<tr>
<td>5,000</td>
<td>2</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>7,000</td>
<td>2</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>7,250</td>
<td>1</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>

LLOT capacity with reservoir level at interim dam crest elevation is 5,800 cfs
Downstream Release

Stochastic Reservoir Reliability Analysis

► New Goal: Decrease magnitude of frequent release through LLOT
The Watershed

Stochastic Reservoir Reliability Analysis

Overall: 380 mi²
Upstream of Anderson Res: 195 mi²
Upstream of Coyote Res: 120 mi²
Operating Rules

Stochastic Reservoir Reliability Analysis

► Refining Valve Hydraulics
Operating Rules Developed Stochastically

Stochastic Reservoir Reliability Analysis

- Operating Rules decrease the frequency of high outflow, while offering high certainty in the reliability of the interim dam

- Flow is routed through various valve openings and initial elevations to determine which opening is required to ensure freeboard is not exceeded.
  - Runs fully open first. If elevation > 560 ft, records failure
  - If < 560 ft, routes through valve openings from 5% to 95% open, in 5% increments
    - If elevation > 560 ft, the next valve opening is checked
    - If elevation < 560 ft, stores the valve opening
Operating Rules: First Trial

Stochastic Reservoir Reliability Analysis

- Required valve openings plotted against corresponding initial elevations and a step function was created to serve as operating rules for the valve.
Operating Rules: First Trial

Maximum Annual Elevation: Initial Operating Rules

Operating Rules Elevation

- Dec-Feb
- Oct-Nov, Mar-Aug

Elev 560

Simulation

Elevation (ft NAVD)
Initial Operating Rule Reliability

<table>
<thead>
<tr>
<th>ELEVATION (FT NAVD)</th>
<th>FAILURE PER 12,000</th>
<th>AEP (%)</th>
<th>RELIABILITY (%)</th>
<th>RISK OF FAILURE 2 Winters (%)</th>
<th>RISK OF FAILURE 3 WINTERS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>540</td>
<td>20</td>
<td>0.17</td>
<td>99.83</td>
<td>0.33</td>
<td>0.50</td>
</tr>
<tr>
<td>545</td>
<td>12</td>
<td>0.10</td>
<td>99.90</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>550</td>
<td>5</td>
<td>0.04</td>
<td>99.96</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>552</td>
<td>3</td>
<td>0.03</td>
<td>99.97</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>560</td>
<td>2</td>
<td>0.02</td>
<td><strong>99.98</strong></td>
<td><strong>0.03</strong></td>
<td><strong>0.05</strong></td>
</tr>
<tr>
<td>565</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>570</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>632</td>
<td>1</td>
<td>0.01</td>
<td>99.99</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>647</td>
<td>0</td>
<td>n/a</td>
<td>---</td>
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</tr>
</tbody>
</table>
## Operating Rules: First Trial

### Stochastic Reservoir Reliability Analysis

#### Re-examining Flow Frequency

<table>
<thead>
<tr>
<th>MAXIMUM RELEASE (CFS)</th>
<th>OCCURRENCES PER 12,000 SIMULATIONS</th>
<th>AEP (%)</th>
<th>PROBABILITY OF RELEASE 2 WINTERS (%)</th>
<th>PROBABILITY OF RELEASE 3 WINTERS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>5,899</td>
<td>49.2</td>
<td>74.2</td>
<td>86.9</td>
</tr>
<tr>
<td>1,500</td>
<td>2,170</td>
<td>18.1</td>
<td>32.9</td>
<td>45.0</td>
</tr>
<tr>
<td>2,000</td>
<td>169</td>
<td>1.41</td>
<td>2.8</td>
<td>4.2</td>
</tr>
<tr>
<td>2,500</td>
<td>55</td>
<td>0.46</td>
<td>0.92</td>
<td>1.4</td>
</tr>
<tr>
<td>3,000</td>
<td>29</td>
<td>0.24</td>
<td>0.48</td>
<td>0.72</td>
</tr>
<tr>
<td>3,500</td>
<td>20</td>
<td>0.17</td>
<td>0.33</td>
<td>0.50</td>
</tr>
<tr>
<td>4,000</td>
<td>5</td>
<td>0.04</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>5,000</td>
<td>2</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>7,250</td>
<td>0</td>
<td>n/a</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
Flow Frequency with Initial Operating Rules

[Graph showing annual exceedance probability against total discharge (cfs) with different operating scenarios: FEMA Operation, Diversion (Fully Open), Diversion (Operating Rules).]
Refining the Operating Rules

Stochastic Reservoir Reliability Analysis

► Refined rules: Revised valve conditions that allow for a higher chance of exceeding freeboard elevation.

► Reliability against freeboard violation: 99.86%

![Graph showing valve opening vs. elevation (ft NAVD)]
Refining the Operating Rules

Stochastic Reservoir Reliability Analysis

► Maximum Annual Elevation: Modified Operating Rules

![Graph showing Modified Operating Rules with elevation in feet NAVD and simulation numbers.]
### Modified Operating Rule Reliability

<table>
<thead>
<tr>
<th>ELEVATION (FT NAVD)</th>
<th>FAILURE PER 12,000</th>
<th>AEP (%)</th>
<th>RELIABILITY (%)</th>
<th>RISK OF FAILURE 2 WINTERS (%)</th>
<th>RISK OF FAILURE 3 WINTERS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>557</td>
<td>24</td>
<td>0.20</td>
<td>99.80</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>560</td>
<td>17</td>
<td>0.14</td>
<td>99.86</td>
<td>0.28</td>
<td>0.42</td>
</tr>
<tr>
<td>565</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>570</td>
<td>2</td>
<td>0.02</td>
<td>99.98</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>631</td>
<td>1</td>
<td>0.01</td>
<td>99.99</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>645</td>
<td>0</td>
<td>n/a</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
Refining the Operating Rules

Stochastic Reservoir Reliability Analysis

Maximum Annual Flow: Modified Operating Rules

Modified Operating Rules Annual Maximum Flow

Discharge (cfs)

Simulation
## Modified Flow Frequency

<table>
<thead>
<tr>
<th>MAXIMUM RELEASE (CFS)</th>
<th>OCCURRENCES PER 12,000 SIMULATIONS</th>
<th>AEP (%)</th>
<th>PROBABILITY OF RELEASE 2 WINTERS (%)</th>
<th>PROBABILITY OF RELEASE 3 WINTERS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>72</td>
<td>0.60</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>1500</td>
<td>41</td>
<td>0.34</td>
<td>0.68</td>
<td>1.0</td>
</tr>
<tr>
<td>2000</td>
<td>17</td>
<td>0.14</td>
<td>0.28</td>
<td>0.42</td>
</tr>
<tr>
<td>3000</td>
<td>17</td>
<td>0.14</td>
<td>0.28</td>
<td>0.42</td>
</tr>
<tr>
<td>4000</td>
<td>17</td>
<td>0.14</td>
<td>0.28</td>
<td>0.42</td>
</tr>
<tr>
<td>5000</td>
<td>17</td>
<td>0.14</td>
<td>0.28</td>
<td>0.42</td>
</tr>
<tr>
<td>5600</td>
<td>11</td>
<td>0.09</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>5650</td>
<td>6</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>6000</td>
<td>2</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>7000</td>
<td>1</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Refining the Operating Rules

Stochastic Reservoir Reliability Analysis

► Flow Frequency with Modified Operating Rules

![Graph showing flow frequency with modified operating rules. The graph plots annual exceedance probability against total discharge (cfs). The lines represent FEMA operation, diversion (fully open), and diversion (operating rules).]
“Expected” starting level established based on max annual elevation from stochastic model results.

Non-Exceedance Probability

Water Surface Elevation (ft NAVD)

Historical Data  Stochastic (Existing Outlet)  Stochastic (Diversion w/Rules)
### Downstream Watershed

#### Downstream 10-year flows in Coyote Creek

<table>
<thead>
<tr>
<th>HMS MODEL REACH</th>
<th>LOCATION</th>
<th>DRAINAGE AREA (SQ MI)</th>
<th>TEN PERCENT DISCHARGE¹ (CFS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Existing²</td>
</tr>
<tr>
<td>COY_R8</td>
<td>Charcot Avenue</td>
<td>320</td>
<td>6,790</td>
</tr>
<tr>
<td>COY_R9</td>
<td>Mobile Homes</td>
<td>319</td>
<td>6,785</td>
</tr>
<tr>
<td>COY_R10</td>
<td>Berryessa Road</td>
<td>318</td>
<td>6,770</td>
</tr>
<tr>
<td>COY_R11</td>
<td>Maybury Road</td>
<td>294</td>
<td>7,210</td>
</tr>
<tr>
<td>COY_R12</td>
<td>Arroyo Road</td>
<td>250</td>
<td>6,480</td>
</tr>
<tr>
<td>COY_R13</td>
<td>Selma Park</td>
<td>249</td>
<td>6,985</td>
</tr>
<tr>
<td>COY_R15</td>
<td>Rock Springs</td>
<td>246</td>
<td>8,510</td>
</tr>
<tr>
<td>COY_R23</td>
<td>Anderson³</td>
<td>195</td>
<td>7,630</td>
</tr>
</tbody>
</table>

1. Listed discharges may reflect creek capacity limitations
2. Existing reservoir outlet/spillway discharge curves
3. Peak releases immediately downstream of Anderson Reservoir
### Downstream 100-year flows in Coyote Creek

<table>
<thead>
<tr>
<th>HMS MODEL REACH</th>
<th>LOCATION</th>
<th>DRAINAGE AREA (SQ MI)</th>
<th>ONE PERCENT DISCHARGE¹ (CFS)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Existing²</td>
<td>LLOW 100% Open</td>
</tr>
<tr>
<td>COY_R8</td>
<td>Charcot Avenue</td>
<td>320</td>
<td>6,845</td>
<td>6,900</td>
</tr>
<tr>
<td>COY_R9</td>
<td>Mobile Homes</td>
<td>319</td>
<td>6,845</td>
<td>6,895</td>
</tr>
<tr>
<td>COY_R10</td>
<td>Berryessa Road</td>
<td>318</td>
<td>6,830</td>
<td>6,875</td>
</tr>
<tr>
<td>COY_R11</td>
<td>Maybury Road</td>
<td>294</td>
<td>7,375</td>
<td>6,440</td>
</tr>
<tr>
<td>COY_R12</td>
<td>Arroyo Road</td>
<td>250</td>
<td>6,845</td>
<td>5,610</td>
</tr>
<tr>
<td>COY_R13</td>
<td>Selma Park</td>
<td>249</td>
<td>6,990</td>
<td>5,610</td>
</tr>
<tr>
<td>COY_R15</td>
<td>Rock Springs</td>
<td>246</td>
<td>9,275</td>
<td>5,575</td>
</tr>
<tr>
<td>COY_R23</td>
<td>Anderson³</td>
<td>195</td>
<td>11,700</td>
<td>4,675</td>
</tr>
</tbody>
</table>

1. Listed discharges may reflect creek capacity limitations
2. Existing reservoir outlet/spillway discharge curves
3. Peak releases immediately downstream of Anderson Reservoir
Next Steps

Stochastic Reservoir Reliability Analysis

- **Interim Operating Rule Curves**
  - Develop final operating rules based on an interim dam overtopping reliability with DSOD and FERC concurrence.
  - Evaluate downstream flood risk during construction with final operating rules.

- **Final Operations Plan**
  - Rule curve based
  - Use forecasts to maintain empty reservoir when safe
  - Emergency Action Plan for construction