Dam Removal Analysis Guidelines for Sediment

ACWI, Subcommittee on Sedimentation

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2017 Federal Engineer of the Year
Acknowledgments

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• Joe Rathbun, Michigan Department of Environmental Quality
• Matt Collins, National Marine Fishery Service
• Tom Augspurger, U.S. Fish and Wildlife Service
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<th>U.S. Department of Agriculture</th>
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<td>Consortium of Universities for the Advancement of Hydrologic Science, Inc.</td>
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<td>Missouri Water Resources Research Research Center</td>
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History of U.S. Dam Construction

Dam Height
National Inventory Dams
- All Dams
- < 4 m
- 4-8 m
- 8-16 m
- 16-32 m
- >32 m

Number of Dams Constructed per Decade

Decades:
- Pre-1810s
- 1810s
- 1820s
- 1830s
- 1840s
- 1850s
- 1860s
- 1870s
- 1880s
- 1890s
- 1900s
- 1910s
- 1920s
- 1930s
- 1940s
- 1950s
- 1960s
- 1970s
- 1980s
- 1990s

Years:
- 1800
- 1810
- 1820
- 1830
- 1840
- 1850
- 1860
- 1870
- 1880
- 1890
- 1900
- 1910
- 1920
- 1930
- 1940
- 1950
- 1960
- 1970
- 1980
- 1990
Over 90,000 major dams in the United States (NID, 2016)

Millions more small dams

1400 dams removed
History of Dam Removal

Heights of Dams Removed

Courtesy of Ryan Bellmore and Jeff Duda, USGS

Cumulative number of dams removed by year

Number of Dams

% Removed

# Removed

# Studied


1944 2014

Number of Dams

0 200 400 600 800 1000 1200

Heights of Dams Removed

< 2m 2-4 m 4-8 m 8-16 m 16-32 m 32-64 m

Percent

0 10 20 30 40 50

Number of Dams

1200
Example Large Dam Removals

• Washington State (fish passage)
  – Glines Canyon Dam (210-feet high)
  – Condit Dam (125-feet high)
  – Elwha Dam (105-feet high)

• Pennsylvania (dam safety)
  – Birch Run Dam (60-feet-high)
  – Logan’s Reserve Pond Dam (59-feet-high)
Reasons for Dam Removal

• River restoration & fish passage
• Dam safety (reduce or eliminate liability)
• Reservoir sedimentation

Common Factor

In nearly all dam removal cases, the original purpose of the dam was no longer being served or the present function of the dam could be met through other means.
When is reservoir sedimentation a big issue for dam removal?
Dam Removal Challenges

• Policy decisions
  – Loss or replacement of project benefits
  – Cultural or historical preservation

• Funding

• Technical
  ▪ Fish passage
  ▪ Dam safety during removal
  ▪ Diversion and care of stream
  ▪ Reservoir sedimentation
  ▪ Uncertainty and adaptive management
New guidelines have been developed for a wide range of dam removals

Gold Hill Dam, Rogue River, OR
Matilija Dam, Matilija Creek, CA
Elwha Dam, Elwha River, WA
Savage Rapids Dam, Rogue River, OR
Chiloquin Dam, Sprague River, OR
Glines Canyon Dam, Elwha River, WA
and a wide range of sediment issues

Chiloquin Dam site

Matilija Reservoir has filled with sediment

Lake Mills delta behind Glines Canyon Dam

Intake sedimentation
Common Sediment Classifications

• Particle grain size
  – Clay (< 0.004 mm)
  – Silt (0.004 to 0.062 mm)
  – Sand (0.062 to 2 mm)
  – Gravel (2 to 32 mm)
  – Cobble (32 to 256 mm)
  – Boulder (> 256 mm)

• Measurement
  – Suspended Load
  – Bed Load

• Transport
  – Wash Load
  – Bed-material load
New Reservoir

Maximum Pool Elevation

Normal Pool Elevation
Reservoir Sedimentation
Full Reservoir Sedimentation

Diagram showing:
- Maximum Pool Elevation
- Full Reservoir Sedimentation
- Delta Sediments
- Lakebed Sediments
- Buried outlet
- Delta deposits
- Lakebed deposits
U.S. Dam Removal Science Initiative

- Heinz Center for Science, Economics and the Environment
Dam Removal Literature Synthesis

• Inter-disciplinary Powell Center Research Synthesis 2014-2015
• Multi-agency and university effort
• Over 100 science-based reports and peer-reviewed literature
U.S. Dam Removal Web Links

- USGS Dam Removal Information Portal (DRIP)
  - [https://www.sciencebase.gov/drip/](https://www.sciencebase.gov/drip/)

- American Rivers (non-profit organization)
  - Technical advice and support for dam removals

- University of California at Berkeley
  - Clearing House for Dam Removal
  - [https://calisphere.org/collections/26143/](https://calisphere.org/collections/26143/)
U.S. Dam Removal Guidelines

• American Society of Civil Engineers
  – Guidelines for Dam Decommissioning (1997)
  – Monograph on Sediment Dynamics upon Dam Removal (2011)
U.S. Dam Removal Guidelines (continued)

- Aspen Institute
  - Dam Removal - A New Option For a New Century (2002)

- U.S. Society on Dams
  - Guidelines for Dam Decommissioning Projects (2015)
    - http://ussdams.org/reports.html#whitepapers
**Dam Removal Resources**

- **U.S. Society on Dams**
  - Guidelines for Dam Decommissioning Projects (2015)
  - [http://ussdams.org/reports.html#whitepapers](http://ussdams.org/reports.html#whitepapers)

- **USGS Dam Removal Information Portal (DRIP)**
  - [https://www.sciencebase.gov/drip/](https://www.sciencebase.gov/drip/)
U.S. Dam Removal Initiatives

• State initiatives
  – Pennsylvania Fish and Boat Commission
  – Wisconsin Department of Natural Resources
  – Massachusetts Executive Office of Energy and Environmental Affairs
  – Oregon Water Enhancement Board
  – Michigan Department of Natural Resources
  – Texas Commission on Environmental Quality
  – New Hampshire
  – Vermont
New Dam Removal Analysis Guidelines for Sediment
New Dam Removal Analysis Guidelines for Sediment

Objective:
Provide a guideline to link the risk of sediment consequences to the level of data collection, analysis, modeling, and sediment management.
Risk is a Key Guideline Concept

• Risk = Probability × Consequence
• Probability is based on reservoir sediment volume relative to mean annual sediment load
• Consequences are based on potential sediment impacts should they occur
• Greater the risk, the greater the level of investigation

Sediment overwhelms water treatment plant during dam removal
Workshops were used to help develop the guidelines

- National experts were invited to two workshops
  - Government
  - Universities
  - Consultants
  - NGOs
Workshop in Portland, Oregon
October 14 - 16, 2008

Field Trip to Marmot Dam
Workshop in State College, Pennsylvania, October 27 - 29, 2009

Field Trip to McCoy Dam
Testing of Analysis Guidelines

• Guidelines were tested and updated using case studies, literature, and latest dam removal results
  – Case studies from across U.S.
  – Negligible to large sediment volumes
  – Range of sediment impact concerns
GUIDELINE PROCEDURES

1. Identify sediment concerns
2. Collect reservoir and river data
3. Evaluate potential for contaminated sediment
4. Determine relative reservoir sediment volume and probability of impact
5. Refine potential sediment consequences and estimate risk
GUIDELINE PROCEDURES

6. Develop dam removal and sediment management alternatives
7. Conduct sediment analysis based on risk
8. Assess uncertainty
9. Determine if sediment impacts are tolerable and, if needed, modify the dam removal & sediment management plans
10. Develop monitoring and adaptive management plan
Sediment analysis flowchart for dam removal (10 Steps)

1. Identify sediment concerns

2. Collect reservoir and river data

3. Evaluate potential for contaminated sediment concerns?
   - NO
   - YES OR UNKNOWN

4. Determine relative reservoir sediment volume & probability of impact
   - Negligible?
     - YES
     - NO Small, Medium, or Large Relative Reservoir Volume

5. Refine potential sediment consequences and estimate risk

6. Develop dam removal and sediment management alternative

7. & 8. Conduct sediment analysis based on risk and assess uncertainty

9a. Sediment impacts tolerable?
   - NO
   - YES

9b. Modify sediment management plan

10. Develop monitoring and adaptive management plan

Sediment Sampling and Analysis
   - Do contaminant concentrations exceed sediment quality criteria?
   - YES
   - NO

Conduct Biological Analysis and Estimate Sensitivity: Can sediments be released?
   - YES
   - NO

Assume cap/isolate and/or full sediment removal

Assess risk of future contaminant release
Sediment analysis flowchart for dam removal

1. Identify sediment concerns

2. Collect reservoir and river data

3. Evaluate potential for contaminated sediment Concerns?
   - NO
   - YES OR UNKNOWN

   Sediment Sampling and Analysis: Do contaminant concentrations exceed sediment quality criteria?
   - NO
   - YES

4. Determine relative reservoir sediment volume & probability of impact
   - Negligible?
   - NO
   - YES

   Conduct Biological Analysis and Estimate Sensitivity: Can sediments be released?
   - YES
   - NO
Sediment analysis flowchart for dam removal

1. Yes
   - DONE with sediment analysis

2. No
   - Small, Medium, or Large Relative Reservoir Volume
     - 5. Refine potential sediment consequences and estimate risk
     - 6. Develop dam removal and sediment management alternative
     - 7. & 8. Conduct sediment analysis based on risk and assess uncertainty

3. Assume cap/isolate and/or full sediment removal

4. Assess risk of future contaminant release
Sediment analysis flowchart for dam removal

6. Develop dam removal and sediment management alternative

7. & 8. Conduct sediment analysis based on risk and assess uncertainty

9a. Sediment impacts tolerable?

9b. Modify sediment management plan

Assess risk of future contaminant release

10. Develop monitoring and adaptive management plan
Iterative Approach

- Start with readily available information
- Repeat analysis steps as more data become available
- Revise dam removal and sediment management plans until impacts are tolerable
# Sediment Analysis Team

**Depends on Complexity**

Knowledge of river hydraulics, sediment transport, and geomorphology

<table>
<thead>
<tr>
<th>Negligible</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
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<td>General knowledge</td>
<td>Expertise</td>
<td>Water quality expertise if contaminants are present</td>
<td>Dam removal experience</td>
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</table>

**Expertise**

- General knowledge
- Water quality expertise if contaminants are present
- Dam removal experience
1. Identify sediment concerns

• Meet with stakeholders to determine project goals and objectives
  – Fish and boat passage
  – Historic preservation
  – Restore reservoir topography and vegetation
  – Downstream sediment load and water quality

• Categorize concerns:
  – Short and long-term concerns
  – Site-specific and reach-scale concerns
2. Collect Reservoir and River Data

- Compile & synthesize available information
  - Site reconnaissance
  - Dam and reservoir operations history
  - Watershed & hydrology
- Conduct reservoir sediment survey
- Collect river data
Characterize Reservoir Sediment

- Volume & spatial distribution
- Grain size (gravel, sand, silt, clay)
- Sedimentation history, including sluicing or dredging
- Buried structures or debris
3. Evaluate Potential for Contaminants

- Determine if contaminants are of concern
- If contaminants are of concern:
  - Sediment samples and chemistry analysis
  - Determine if concentrations exceed criteria
  - If so, conduct biological analysis
- Management options for contaminants:
  - Cap & isolate
  - Remove & dispose

Milltown Dam, MT (EPA)
4. Determine Relative Reservoir Sediment Volume and Probability of Impact

• Estimate the average annual sediment load
  – Daily sediment load measurements
  – Sediment yield estimate
  – Cases where reservoir still traps sediment
  – Sediment-discharge rating curve

• Estimate the probability of sediment impact
Probability of Sediment Impact

\[ T_s = \frac{V_s \text{ or } M_s}{Q_s} \]

- **\( T_s \)** = years of trapped sediment load
- **\( V_s \) or \( M_s \)** = reservoir sediment volume or mass
- **\( Q_s \)** = mean annual sediment load

<table>
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<th>Years of Reservoir Sediment Storage</th>
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<td>Negligible</td>
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Criteria for Negligible Reservoir Sediment Volume

- Alternate criteria for low-head dams operated as run-of-the river:
  - Sediment volume less than a sand or gravel bar
    - $V_{sed} < W_B^2 D_B$
  - $W_B$ & $D_B$ are the average bankfull channel width and depth
  - If true, no further sediment analysis recommended
Tips for Reservoir Sediment Volume Estimates

• Try and find predam photographs
• Estimate reservoir sediment trap efficiency for fines
• Determine if the reservoir is still accumulating sediment
• Check the operational history for frequent draw downs
Fine Reservoir Sediment Trap Efficiency

\[ K = SI \text{(sedimentation index)} \times g \text{(gravitational acceleration)} \]

Brune (1953) and Churchill (1948)

Ratio of reservoir size to mean annual inflow

Brune medium curve

Churchill trap efficiency

\[ \% = 100 - (1600K^{-0.2} - 12) \]

Reservoir trap efficiency

Brune (1953) and Churchill (1948)

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<td>Lake Corpus Christi</td>
<td>1942–1948</td>
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<td>Fort Supply Reservoir</td>
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<td>John Martin</td>
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<td>○−3</td>
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Tips for Reservoir Sediment Volume Estimates

- Perform bathymetric survey and compare with previous surveys, if available
- Reservoir drawdown test to expose and incise sediment
- Drill or probe sediment to measure thickness and size gradation
- Compare river and reservoir longitudinal profiles
5. Refine Potential Sediment-related Consequences and Estimate Risk

- Identify consequences
  - Fine & coarse sediment
  - Location, timing & duration of impact
  - Short term & long term
- Rank consequences
  - Low, Medium, or Large
- Compute risk of sediment impact
Potential Sediment Issues

- Temporary increase in suspended sediment concentration and turbidity
- Riverbed sediment deposition, increased flood stage, and temporary impairment of aquatic habitat
- Sediment burial of water intakes
- Downstream sediment deposition in coastal or lake delta
Risk Estimates

- Risk = Probability × Consequence

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<th>Consequence of Sediment Impact</th>
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<td>High Risk</td>
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6. Develop Dam Removal and Sediment Management Alternatives

- Develop the dam removal plan
  - Full or partial dam removal
  - Rapid or phased dam removal
  - Removal during certain seasons or flows
6. Develop Dam Removal and Sediment Management Alternatives

• Develop sediment management alternatives
  – River Erosion
  – Mechanical Removal
  – Reservoir Stabilization
River Erosion

- River is allowed to erode a channel through the reservoir sediments
- The rate of erosion depends on the rate of reservoir drawdown
- Most commonly adopted alternative
- Least cost, but maximum turbidity and downstream deposition
A narrow pilot channel may be desired for wide reservoirs

Based on laboratory modeling by Chris Bromley
Mechanical Removal

• Sediments are removed from the reservoir
• Options include:
  – Hydraulic dredge and slurry pipeline
  – Mechanical excavation and truck transport
• High cost, but prevents sediment from entering the downstream river channel.
Reservoir Stabilization

Excavated sediment

Bank protection
Reservoir Revegetation

- Control exotic species
- Avoid planting in unstable areas
- New growth depends on moisture and seed availability
7. Conduct Sediment Analysis Based on Risk

- Develop conceptual model
  - Qualitatively describe what will happen to the reservoir sediment and what the reservoir topography will look like
Reservoir Conceptual Model

(a) Pre-removal reservoir

(b) Dewatering immediately following removal

(c) Degradation

(d) Degradation and widening
Reservoir Conceptual Model

(e) Aggradation and Widening

(f) Degradation and Widening
   (High Streampower)

(f) Aggradation and Narrowing

(g) Quasi-equilibrium
## Variations in Lateral Erosion

| Valley-wide erosion in coarse, non-cohesive sediment | Narrow incision through fine, cohesive sediment |

Lake Mills delta, Elwha River, WA
# Sediment Impact Risk & Analysis Tools

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<td><strong>Simple Computations</strong></td>
<td>Conceptual Model</td>
<td>Total Stream Power</td>
<td>Geomorphic Analysis</td>
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<td>Mass Balance &amp; Empirical Estimates</td>
<td>Sediment Wave Model</td>
<td>Sediment Transport Capacity</td>
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<td>Numerical or Phys. Model, Field Test</td>
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</table>
7. Conduct Sediment Analysis Based on Risk

• Special considerations
  – Climate change
    • Removal of run-of-the river dams would not affect hydrology
  – Multiple dam removals
    • Depends on the sequencing of dam removal
8. Assess uncertainty of Predictions

• Observational Uncertainties
  – Reservoir sediment volume
  – Grain sizes and spatial distribution
  – Contaminant concentrations
  – Future stream flow hydrograph
• Parameter Uncertainty
  – Roughness, reference shear stress
• Model structure uncertainty
• What could happen that you haven’t thought of?
9. Determine if Sediment Impacts are Tolerable

- Assess predicted impacts & uncertainty
- Determine if impacts are tolerable or if they can they be avoided or mitigated
- If uncertainty is too high, addition data collection, analysis, and modeling
- If impacts are too high, modify dam removal & sediment management plans
Modify Management Plans

• Incremental or phased dam removal
• Change timing of dam removal
• Reduce reservoir sediment erosion
  – Remove or stabilize sediment prior to dam removal
  – Leave a portion of the dam in place
• Install wells or infiltration galleries
• Enhance or build Water treatment plants
• Raise or construct flood levees
10. Develop Monitoring and Adaptive Management Plan

- Use predictions to guide monitoring plan
- Devise real-time monitoring
- If monitoring results differ from predictions, determine why
- If necessary, adapt implementation to ensure that impacts are tolerable
Dam Removal Analysis Guidelines for Sediment

Advisory Committee on Water Information
Subcommittee on Sedimentation

Available free at https://acwi.gov/sos/
Conclusions

• Guidelines relate the level of sediment data collection, analysis, modeling and mitigation to risk

• Users are encouraged to apply the guidelines in an iterative process

• Inter-disciplinary collaboration is always recommended

• Frequent communication among team and stakeholders
EXAMPLE CASE STUDIES

Gold Hill Dam, OR

Chiloquin Dam, OR

Savage Rapids Dam, OR
Gold Hill Dam Removal
Rogue River, Oregon (RM 121)

- Run of river operation
- Supplied municipal and industrial water
- Concrete diversion dam
  - 1 to 8 feet high
  - “L” plan shape
  - 1,000-foot crest
- Reservoir pool
  - 350 feet wide
  - 1 mile long
  - 100 acre feet
Dam Removal Objective

Replace water diversion with pump to restore fish passage
Negligible Sediment Risk

• Reservoir had little to no trap efficiency
• Divers found only 456 yd³ of silt and clay, much less than an average annual sediment load and easily transported by river
• Cofferdam required more sediment than stored in reservoir
Dam Removal & Sediment Management

- Full vs partial dam removal considered
- Sediment Management - Minimal
  - No presence of contaminants
  - No probability of downstream aggradation
  - Low probability of increased sediment concentrations during removal that would affect habitat
Survey and Hydraulic Modeling

- Survey predicted low-flow path and water depths at new pump location for design.
- Modeling of velocities indicated that full dam removal (rather than partial) would guarantee successful fish passage.
- Project cost comparisons concluded removing entire dam versus only a portion increased total project costs by only 4%.
Gold Hill Following Removal
Chiloquin Dam Removal
Sprague River, Oregon

- Run of river operation
- Supplied irrigation water
- Concrete diversion dam
  - 11-foot hydraulic height
  - 100-foot crest length
- Reservoir pool
  - 100 to 200 feet wide
  - 3,600 feet long
  - Very little sediment trap efficiency.
Project Objectives

• Restore fish passage for the endangered Lost River Sucker and Shortnose Sucker.
• Provide water for the Modoc Point Irrigation District with modern fish screens.
Reservoir Sediment Volume Estimates

Planimetric Area Method:
Surface area × thickness

Sediment thickness estimated by divers

Reservoir Sediment Areas

- 153,000 ft²
  5 ft thick
- 105,000 ft²
  2 ft thick

Total Channel Sediment Volume of
36,000 yds³
49,000 tons
Reservoir Sediment Volume Estimates

Cross-Section Method:
Sediment cross-sectional area × longitudinal distance

Estimated sediment volume of 45,000 yd$^3$ (61,000 tons)
Mean-annual Sediment Load Estimate

River Hydraulic Capacity to Transport Sediment

- d50 = 0.25 mm
- d50 = 0.5 mm

206,000 to 315,000 tons/yr
Low Sediment Risk

• Small Sediment Probability
  – Sediment mass is 20% to 30% of the river’s mean annual sediment transport capacity.

• Potential Consequences
  – Sediment deposition on spawning riffles
  – Sediment deposition along Williamson River near Klamath Lake
Dam Removal & Sediment Management

• Dam was entirely removed
• No Sediment Management
Chiloquin Dam Following Removal

July and August 2008

- Less reservoir sediment than expected
- Sawed logs submerged in the reservoir were discovered after dam removal
Savage Rapids Dam Removal
Rogue River, Oregon (RM)

• Run of river operation
• Diverts irrigation water April to October
• Concrete diversion dam
  ▪ 39 feet high
  ▪ 464-foot crest
• Reservoir pool
  ▪ 290 to 370 feet wide
  ▪ 3000 ft long
  ▪ 300 acre-feet
Dam Removal Objective

- Improve fish passage for both upstream adult and downstream juvenile migration
- Pumping plant to replace the function of the existing dam
Moderate Sediment Risk

• Medium Sediment Probability
  – 2/3 sand and 1/3 gravel; less than 2% silt/clay
  – 1 to 2 years average annual load

• Potential Consequences
  – Release of possible contaminants
  – Burial of two downstream water intakes
  – Burial of downstream fish habitat
  – Partial removal may not provide full fish passage
  – Full removal could bury new water intake
Implementation Plan

• Partial Dam Removal
  – Partial dam removal to protect new downstream water intake and plant
  – Ensure anadromous fish passage maintained during majority of removal

• River Erosion Sediment Management
  – No contaminants
  – Lower reservoir through radial and construct cofferdam
  – Remove dam behind cofferdam in two phases
  – Excavate pilot channel reservoir sediment
Conceptual Model

- Fine sediment (<2%) not expected to affect water quality beyond dam removal
- Reservoir width only 2 to 3 times greater than river width
- Sand and gravel expected to fill downstream pools
- River has high transport capacity downstream of dam site.
- Large downstream tributary.
Analysis Questions

• Where should new pumping plant intake be located?

• What are impacts from release of reservoir sediment?

• How should dam be removed?
Analysis: Fish Passage During Dam Removal, $V < \text{ than } 10$ ft/s
How did it turn out?

- Short-term turbidity increase within range of natural flood
- Fish passage maintained
- Temporary burial of new water intake during dry winter
- Required excavation until 2-year flood
- Water intake 5 miles downstream had short-term increase in treatment cost
Short Duration Turbidity Impacts

Turbidity 2.3 miles upstream of dam
Turbidity 0.3 miles downstream of dam
Discharge 5 miles downstream of dam

10-09-09 10:15 AM
Breaching of sediment bar

Turbidity Exceeded:
100 FNU for 3 hours
50 FNU for 7 hours
7 FNU for 3 days


0 2,000 4,000 6,000 8,000 10,000
0 50 100 150 200 250

Turbidity (FNU)
Discharge (cfs)
Channel Modification

- Old timber crib found that had to be removed (one day of work)
- Irregular bedrock along channel margin had to have minor excavation to create thalweg path toward intake (one day of work)
Savage Rapids Pumping Plant Construction in preparation for dam removal
Savage Rapids Pumping Plant

Completed before preparation for dam removal
Savage Rapids Following Removal