MANAGEMENT OF IMPOUNDED RIVERS
(Part 3)
Zhao-Yin Wang
and
Steve Melching
7.4 Dam failure and dam removal

- **7.4.1 DAM FAILURE**
  - Throughout history, dam incidents and dam failures have inflicted tremendous loss of lives, as well as great damage to properties.
  - Dam failure may be caused by extreme events due to intense rainfall from thunderstorms and from extreme weather such as hurricanes, massive landslides and landslide induced waves in the river, volcanic eruptions, and fires which could damage the outlet control structure and make difficult the operation of the spillways.
  - Regardless of the types of dam construction and direct causes, when a dam fails, huge quantities of water rush downstream with great destructive force.
Table 7.11  Number of dam failure and failure Rate in of dam failure of a few countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Source</th>
<th>Number of dam failure</th>
<th>Number of dams in statistics</th>
<th>Time of statistics (years)</th>
<th>Rate of dam failure (1/dam.year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>Gruner, 1963, 1967</td>
<td>33</td>
<td>1764</td>
<td>40</td>
<td>$5 \times 10^{-4}$</td>
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<tr>
<td>U.S.</td>
<td>Post-1940 dams</td>
<td>12</td>
<td>3100</td>
<td>14</td>
<td>$3 \times 10^{-4}$</td>
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<tr>
<td>U.S.</td>
<td>USCOLD, 1975</td>
<td>74</td>
<td>4914</td>
<td>23</td>
<td>$7 \times 10^{-4}$</td>
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<tr>
<td>U.S.</td>
<td>US Department of Reclamation</td>
<td>1</td>
<td>4500</td>
<td></td>
<td>$2 \times 10^{-4}$</td>
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<tr>
<td>U.S.</td>
<td>Mark and Stuart-Alexander, 1977</td>
<td>125</td>
<td>7500</td>
<td>40</td>
<td>$4 \times 10^{-4}$</td>
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<tr>
<td></td>
<td>Middlebrooks, 1953</td>
<td>9</td>
<td>7833</td>
<td>6</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Japan</td>
<td>Takase, 1967</td>
<td>1046</td>
<td>$2 \times 10^6$</td>
<td>15</td>
<td>$4 \times 10^{-5}$</td>
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<tr>
<td>Spain</td>
<td>Gruner, 1967</td>
<td>150</td>
<td>1620</td>
<td>145</td>
<td>$6 \times 10^{-4}$</td>
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<tr>
<td>China</td>
<td>Nankin Institute of Water Resources and Hydro-power</td>
<td>3462</td>
<td>85120</td>
<td>47</td>
<td>$8.65 \times 10^{-4}$</td>
</tr>
<tr>
<td>China</td>
<td>IWHR</td>
<td>3481</td>
<td>85153</td>
<td>50</td>
<td>$8.18 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Typical Examples of dam failure events and loss of lives and properties

<table>
<thead>
<tr>
<th>Dam</th>
<th>Country</th>
<th>Time of failure</th>
<th>Casualties (p)</th>
<th>Economic loss (million dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puentes</td>
<td>Spain</td>
<td>1802-04-30</td>
<td>600</td>
<td>1.0</td>
</tr>
<tr>
<td>South Fork</td>
<td>U.S.</td>
<td>1889-05-31</td>
<td>2200</td>
<td>100.0</td>
</tr>
<tr>
<td>Saint Francis</td>
<td>U.S.</td>
<td>1928-03-13</td>
<td>450</td>
<td>1.5</td>
</tr>
<tr>
<td>Veg de Tera</td>
<td>Spain</td>
<td>1959-01-10</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>Malpasset</td>
<td>France</td>
<td>1959-12</td>
<td>421 (death)</td>
<td>68.0</td>
</tr>
<tr>
<td>Oros</td>
<td>Brazil</td>
<td>1960-03-25</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Babii Yar</td>
<td>USSR</td>
<td>1961-03</td>
<td>145</td>
<td>4.0</td>
</tr>
<tr>
<td>Hyokiri</td>
<td>North Korea</td>
<td>1961-07</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Quebrada La Chapa</td>
<td>Columbia</td>
<td>1963-04</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Vaiont</td>
<td>Italy</td>
<td>1963-10-9</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Baldwin Hills</td>
<td>U.S.</td>
<td>1963-12-14</td>
<td>3</td>
<td>50.0</td>
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<tr>
<td>Mayfield</td>
<td>U.S.</td>
<td>1965</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Vratsa</td>
<td>Bulgaria</td>
<td>1966-05-01</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Nanak Sagar</td>
<td>India</td>
<td>1967-09-08</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Sempor</td>
<td>Indonisia</td>
<td>1967-12-01</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Pardo</td>
<td>Argentina</td>
<td>1970</td>
<td></td>
<td>20.0</td>
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</table>
# Table 7.13 Dam failure events in China

<table>
<thead>
<tr>
<th>Dam / Province</th>
<th>Time of dam failure (Month-date-year)</th>
<th>Casualties (death toll)</th>
<th>Loss of properties</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lomngtun / Liaoning</td>
<td>07-21-1959</td>
<td>35428 (707 death)</td>
<td>25,942 hauses, 14,210 ha farmland</td>
<td>Huang, 1988</td>
</tr>
<tr>
<td>Tiefosi / Henan</td>
<td>05-18-1960</td>
<td>1,662 (1,092 death)</td>
<td>7,102 hauses</td>
<td>Huang, 1988</td>
</tr>
<tr>
<td>Liujiatai / Hebei</td>
<td>08-08-1963</td>
<td>(948 death)</td>
<td>67,721 hauses, 1,587 ha farmland</td>
<td>WMRP, 1981</td>
</tr>
<tr>
<td>Hengjiang / Guangdong</td>
<td>09-15-1970</td>
<td>(779 death)</td>
<td>66,600 ha farmland</td>
<td>Huang, 1988</td>
</tr>
<tr>
<td>Lijiazui / Gansu</td>
<td>04-27-1973</td>
<td>(580 death)</td>
<td>1,133 ha farmland, 1,000 ha farmland</td>
<td>Huang, 1988</td>
</tr>
<tr>
<td>Shijiagou / Gansu</td>
<td>08-24-1973</td>
<td>146 (81 death)</td>
<td>298 hauses, 40 ha farmland</td>
<td>Huang, 1988</td>
</tr>
<tr>
<td>Banqiao and Shimantan / Henan</td>
<td>108-08-1975</td>
<td>10.155 million (26,000 death)</td>
<td>5.24 million hauses, 1.13 million ha farmland</td>
<td>Henan Provincial Department of Water Resources, 2005</td>
</tr>
<tr>
<td>Gouhou / Qinghai</td>
<td>08-27-1993</td>
<td>(288 death)</td>
<td>($18.5 million U.S. dollars)</td>
<td>Huang, 1988</td>
</tr>
</tbody>
</table>
Fig. 7.21 Number of dam failures in the period from 1954 to 2003 in China (Dams in Taiwan are not included) (He and Wang et al., 2007)
Fig. 7.22 Distribution of spectral density of dam failure events
**Fig. 7.23** Distributions of the number of the sunspots and the number of dam failure events in the period from 1954-2005.
Fig. 7.24 Percentages of dam failures for different age groups
• in China and other countries
**Fig. 7.25** Percentage of different age groups of dam failures in Russia in comparison with the failures of world dams
• Fig. 7.26 Spatial distribution of dam failure rate in China
• based on statistics of dam failure events in provinces (He et al., 2007)
1) The periods of dam failure events are 24 years and 12 years, which is similar to the average period of sunspots activities.

2) The peak of dam failure events occurs during the sunspots activities “declining period”.

3) During the first 5 years of operation, the probability of dam failure is higher.

4) In China, the dam failure rate in the area north to or near the 400mm annual precipitation line is notably higher than the area south to the line; the dam failure events in a area is higher after the area experiencing a long period of drought.

5) For the areas where the annual precipitation is low and the flood season relatively dry, the risk of dam failure is high.

6) For the areas with large temperature difference in different seasons, the risk of dam failure is high.
Dam Removal
Dams in the U.S.

- More than 75,000 dams more than 2 m high
- 950,000 km of waterways obstructed
- Only about 3% have turbines
- 1,800 of these dams are officially deemed unsafe
- By 2020, 85% of all government owned dams will be at least 50 years old
Ecological Effects of Dams

- Dams obstruct river flows, alter nutrient cycles, block fish migration, and disrupt temperature regimes and dissolved oxygen levels favorable to aquatic life.
- Prime habitat is commonly lost, and exotic fish species are introduced.
Dam Relicensing

- Private hydropower dam owners seek to renew 30- to 50-year operation agreements with the FERC
- Process is forcing dam owners, government decision makers, and affected communities to re-evaluate the costs and benefits of dams, especially in light of mandates to...
Dam Relicensing

- Protect endangered species
- Recognize tribal fishing rights
- Give “equal consideration” to fisheries, recreation, and environmental quality

In a growing number of cases, removal of dams represents the best river management option.
Cost Benefits

- Removal costs of 70 small dams in Wisconsin were found to be an average of 2-5 times less than estimated repair costs.
- On the Baraboo River, Wisconsin, the cost of removing the 3-m high Oak Street Dam was $30,000, compared to repair estimates of $300,000.
- In Maine, removal costs for the 8-m high Edwards Dam were roughly one third of the $9 million price tag of upgrading fish ladders.
Fishery Benefits

• One year after the 1999 Edwards Dam removal, migratory fish returned in abundance to previously impounded parts of the Kennebec River

• Fish diversity in the Baraboo River more than doubled, from 11 to 24 species, just 18 months after restoration of free-flowing conditions

• 2 years after removal of a dam on Tea Creek, the number of trout soared to more than 6 times the population necessary to reach “Class A”
Dam Removal in Wisconsin

• Approximately 100 dams removed since 1967 only 4 greater than 15-m high

• Reasons
  1) Removal of an unsafe structure
  2) Removal of “abandoned” dams when either no owner is found or the owner is unable to fund repairs
  3) Removed because of significant environmental impact
Dam Removal in the U.S.

• Most of the 500 documented dam removals (through ) in the U.S. involved dams less than 12-m high
• 177 dam removals in the 1990s
• 185 since 1999
• White Salmon River, Washington:
  38-m high Condit Dam will be removed at a cost of $15 million (adding modern fish ladders and other improvements would have cost more than $30 million)
Dam Removal in the U.S.

- Elwha River, Washington (to begin in 2008): 32-m high Elwha Dam and 82-m high Glines Canyon Dam
  - Private dams, now within the Olympic Peninsula National Park
  - In 1992, the government heeded tribal demands to provide “full restoration” of the river, including dam removal
  - Removal activities are estimated to cost at least $100 million
Elwha and Glines Canyon Dams
HOW TO TEAR DOWN A DAM
Deconstruction of the Elwha Dam will be the most complex part of the three-year project.

**PHASE 1**
Open the four spillway gates on the south side of the dam to lower the level of the Lake Aldwell reservoir 18 ft. (1 month)

**PHASE 2**
Remove the south gates and dig a diversion channel. Blast a 30 x 35-ft. plug of bedrock in five stages and reroute the river through the gap. (3 months)

**PHASE 3**
Take out the north spillway and upper portion of the dam and install a 12-ft.-wide road in order to access the penstock tubes. (1 month)

**PHASE 4**
Remove steel penstocks and slide gates, the concrete intake structure and powerhouse—not shown. (5 months)

**PHASE 5**
Haul out 200,000 cubic yards of rock, earth, concrete and fill trees that were placed behind the gravity dam after a 1913 burst. (8 months)

**PHASE 6**
Remove the concrete gravity dam 7 to 10 ft. at a time using explosives, and restore the natural river channel. (2 months)
Dam removal in other countries

- **France** - Inspired in part by decommissioning efforts on the Elwha River in the US, the Loire Vivante (Living Loire) network is working to remove old dams and restore France’s only remaining river that supports native salmon.

- In 1998, the 12–meter–high Saint–Etienne–du–Vigan Dam on the Upper Allier was removed, marking the first case in which France’s state–owned electricity utility destroyed a dam to restore salmon habitat.

- The Vienne River, the second largest Loire tributary, also flows freely now after demolition of the 4–meter–high Maisons–Rouges Dam.

- Dam removal in France and the Loire River management plan reflect growing awareness across Europe.
Dam removal in Czech Republic

• Since 1991, local NGOs and concerned citizens have campaigned to remove three small dams that flooded 1,300 acres of riparian and woodlands habitat along the Morava and Dyje rivers.

• The Ramsar Convention, which lists the affected area as a wetland of international importance, obliges the Czech Government to maintain the ecological character of the site.

• Czech conservation groups such as the Ecological Institute Veronica continue to demand decommissioning of the Nove Mlyny dams and further restoration efforts in the area.
Dam removal in Thailand

• In Thailand, decommissioning campaigns have arisen as a result of social and ecological disruptions caused by dam construction on the Mun River, the largest tributary of the Mekong.

• The 135–MW Pak Mun Dam was funded by the World Bank and completed in 1994. As a direct result of the dam, more than 20,000 people have been affected by drastic reductions in fish populations upstream of the dam site, and other changes to their livelihoods. Villagers occupied the dam site and are demanding that dam gates be permanently opened to allow fish migration.
Sediment Management for Dam Removals
Why Do We Care?

- Project Cost
- Permitting
- Environmental Concerns
- Liability
- Project Performance
  - Aesthetics
  - Recreational Use
  - Economic

Relative Magnitude of Costs for Dam Removal
Elwha River, WA (Morris & Fan, 1997)
Purpose Of Presentation

• *Briefly* Describe Physical Process of Sedimentation

• *Briefly* Describe Options for Sediment Management for Dam Removal

• Some Data on Short-Term Impacts of Dam Removal on Downstream TSS

• Summary of Tools Needed to Ensure Responsible Dam Removal Sediment Management
Sedimentation Patterns Related to Several Conditions

- *Hydrologic Conditions*
- *Stream Inlet Locations*
- *Sediment Characteristics*
- *Reservoir Geometry*
- *Outlet Design*
- *Operating Rule*
Longitudinal Deposit Geometry

Delta

Tapering

Wedge

Uniform

Morris & Fan, 1997
Physical Process of Sedimentation

*Pre-Dam Conditions*

Sediment Transport
Continuity
Physical Process of Sedimentation

New-Reservoir Conditions

Interruption of Sediment Transport
Physical Process of Sedimentation

*Young Reservoir Conditions*

Coarser Sediment Drops Out at Upstream Limits
Physical Process of Sedimentation

As the Reservoir Ages

- Sediment Delta Progresses Downstream
- Finer Sediment Deposited Near the Dam Face
Physical Process of Sedimentation

*As the Reservoir Ages*

- Sediment Delta Progresses Downstream
- Finer Sediment Deposited Near the Dam Face
Physical Process of Sedimentation

As the Reservoir Ages

- Sediment Delta Progresses Downstream
- Finer Sediment Deposited Near the Dam Face
Physical Process of Sedimentation

Aged Reservoir

- Equilibrium is Reached
- Sediment Layers

  Finer Material Covered by Coarser Material

  Consolidation of Material
Impacts of Sediment Release

- Fisheries
- Benthic Organisms
- Municipal Water Supply
- Industrial / Agricultural Uses
- Water Treatment
- Morphology
- Conveyance Capacity
Deterministic Tools Are Limited

• Stochastic Phenomenon

• Dam Removal Similar to Flushing Operations Used for Reservoir Sediment Management
  • Widely Used in France for Inspection
  • Used in China as Part of Rule of Operation
  • Published Data is Limited and Project Specific
Sediment Management Approaches for Dam Removal

• Minimal Management

• In-Place Stabilization

• Time Stepped Approach

• Excavation and Stabilization of Reservoir Sediments
Two Extremes in Timescale Yield Two Extremes in Sediment Management

*Geologic Time Scale*
This Leads to the “Rip ‘n Run”
## Minimal Management

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Concerns</th>
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<tbody>
<tr>
<td>Cheaper than Active Management of Sediment</td>
<td>Degraded Stream Reach</td>
</tr>
<tr>
<td>Easier to Design</td>
<td>Downstream Impacts</td>
</tr>
<tr>
<td>No Long-Term Construction and Monitoring</td>
<td>Aesthetics</td>
</tr>
<tr>
<td>Allows More Dams to be Removed</td>
<td>Social Impacts</td>
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</table>
Engineering Time Scale
Leads to a “Full-Restoration”
## Full Restoration

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restores Ecological Function Quickly</td>
<td>Resource Competition Delays</td>
</tr>
<tr>
<td></td>
<td>Other Dam Removals</td>
</tr>
<tr>
<td>Aesthetic</td>
<td>$$’s</td>
</tr>
<tr>
<td>Social Benefits</td>
<td></td>
</tr>
<tr>
<td>Restores Capability of Stream to Adapt</td>
<td></td>
</tr>
<tr>
<td>Engineering Objectives Can Be Met</td>
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Choices within the Extremes
In-Place Stabilization by Constructing an Over-Steepened Transition Channel or a Series of Transitions

Ramp – Steep Channel
Step-Pool Series of Drops
<table>
<thead>
<tr>
<th>Advantages</th>
<th>Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initially Cheaper than ‘Full-Restoration’</td>
<td>Is this River Restoration?</td>
</tr>
<tr>
<td></td>
<td>Responsiveness</td>
</tr>
<tr>
<td>Provides Some Short-Term Function</td>
<td>Design Components / Design Standards</td>
</tr>
<tr>
<td>Aesthetic Benefits</td>
<td>Life-Cycle Costs / Maintenance</td>
</tr>
<tr>
<td>Minimizes Floodplain Sediment Migration (Contaminated Sediment)</td>
<td></td>
</tr>
</tbody>
</table>
Time-Stepped Approach Dam Removal
Time-Stepped Approach Dam Removal

Open Lower Gate
Time-Stepped Approach Dam Removal
Time-Stepped Approach Dam Removal
Time-Stepped Approach Dam Removal
# Time-Stepped Removal

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreads the Impact Over Time – Allows Downstream</td>
<td>Does Not Explicitly Address Floodplain Sediment Removal</td>
</tr>
<tr>
<td>Natural Communities to Adapt</td>
<td></td>
</tr>
<tr>
<td>Allows Floodplain Sediments to Dewater, Aerate,</td>
<td>Still Have An Incised System – Can Get Stabilized by Vegetation</td>
</tr>
<tr>
<td>Consolidate, Vegetate</td>
<td>Establishment Delaying Eventual “Natural Rehabilitation”</td>
</tr>
<tr>
<td>Can Monitor Downstream Impacts During Process</td>
<td></td>
</tr>
</tbody>
</table>
Impact of Storm Event on Channel Substrate Following Dam Removal

*Baraboo, WI*

![Graph showing sediment composition](image)

**Fig. 5.** Relative composition (as % of total sample mass) of sediment size fractions along a longitudinal transect from 364 m above to 1090 m below the Dam #1, removed site (0 m), March and August 2000. Sediment for individual sampling points are indicated on the y-axis. Fine sediments <0.05 mm, sand = 0.05-2.0 mm, gravel >2.0 mm.

*(Stanley, Luebke, Doyle, Marshall, 2002)*
Short-Term Impacts of Dam Removal on TSS

*Two Case Studies*

- Mill Pond Dam on the Pomme de Terre River
- Frazee Dam on the Otter Tail River
Appleton Mill Pond
Dam Removal Case History

Pomme de Terre River in Western Minnesota
Provided Power for Local Mill Site
Concrete Rubble Dam
Dam Ht = 17 ft (5.2 m)
Dam Length = 157 ft (48 m)
Size of Reservoir = 57 ac (23 ha)
D.A. = 907 mi² (2,350 km²)
Removed in Winter 1998
Appleton Dam Before Removal
Aerial Photo of Appleton Dam’s Pool
Appleton Dam After Removal
Frazee Dam Removal Case

History

Otter Tail River in Northwest Minnesota

Dam Ht = 19 ft (5.8 m)

Dam Length = 60 ft (18.3 m)

D.A. = 237.7 mi² (616 km²)

Removed in Winter 1998
Frazee Dam Location

Frazee Dam
On the Otter Tail River

Sampling Location Upstream of Dam
Sampling Location Downstream of Dam
Frazee Dam Before Removal
Aerial Photo of Frazee Dam Pool Before Removal
Frazee Dam Site After Removal
T.H. 87 Crossing Upstream of Dam Site
Progression of Frazee Pool

Spring Before Removal
Progression of Frazee Pool

*Fall Before Removal*
Progression of Frazee Pool

*Winter During Removal*
Progression of Frazee Pool
Spring After Removal
Progression of Frazee Pool

*Summer After Removal*
Impact of Dam Removal on Water Quality Was Measured

Total Suspended Solids (TSS) Concentrations were Measured Using a Depth Integrated Sampler
Results of Water Quality Sampling

MILL POND DAM ON THE POMME DE TERRE RIVER

Dam Removed 02/24/99 to 03/19/99

Total Suspended Solids (TSS) in mg/l

- Yellow: Upstream of Dam at US Hwy 59
- Red: Downstream of Dam at USGS Gage

Sample Collection Date

No Sample Taken Upstream at US Hwy 59 on 2/26/99 and 3/10/99 Due to Ice
Results of Water Quality Sampling

FRAZEE DAM ON THE OTTER TAIL RIVER

Dam Removed 02/22/99 to 03/04/99

Total Suspended Solids (TSS) in mg/l

- T.H. 87 - Upstream of Dam
- Just Below Dam Near CSAH 30
- US Hwy 10 - Downstream of Dam

Sample Collection Date

02/09/99 02/25/99 02/26/99 03/01/99 03/04/99 04/21/99 05/05/99 07/14/99

Note: Grab Sample Taken at 36” Storm Sewer Outlet on 05/05/99 = 2,100 mg/l
Comparison of Measured TSS Values

A Grab Sample Taken At Frazee (2,100 mg/l)
Conclusions – Tools Needed

• Ensure Sufficient **Flexibility in Permitting Rules** to Treat Dam Removal as a *Component* of River Restoration /Management
  • Risk-Based
  • Site / Project Specific with an Understanding of Overall Goals

• Ensure **Flexibility in Funding** Allows Different Approaches

• Ensure Dam Removal **Design Incorporates a Specific Strategy** to Meet Specific Project Goals

• **Include a Monitoring Component of Dam Removal** - Collect and Publish More Data Regarding Dam Removal (Morphology, Short/Long Term Sediment Concentration, Fisheries, Macroinvertebrate, Water Quality, etc)