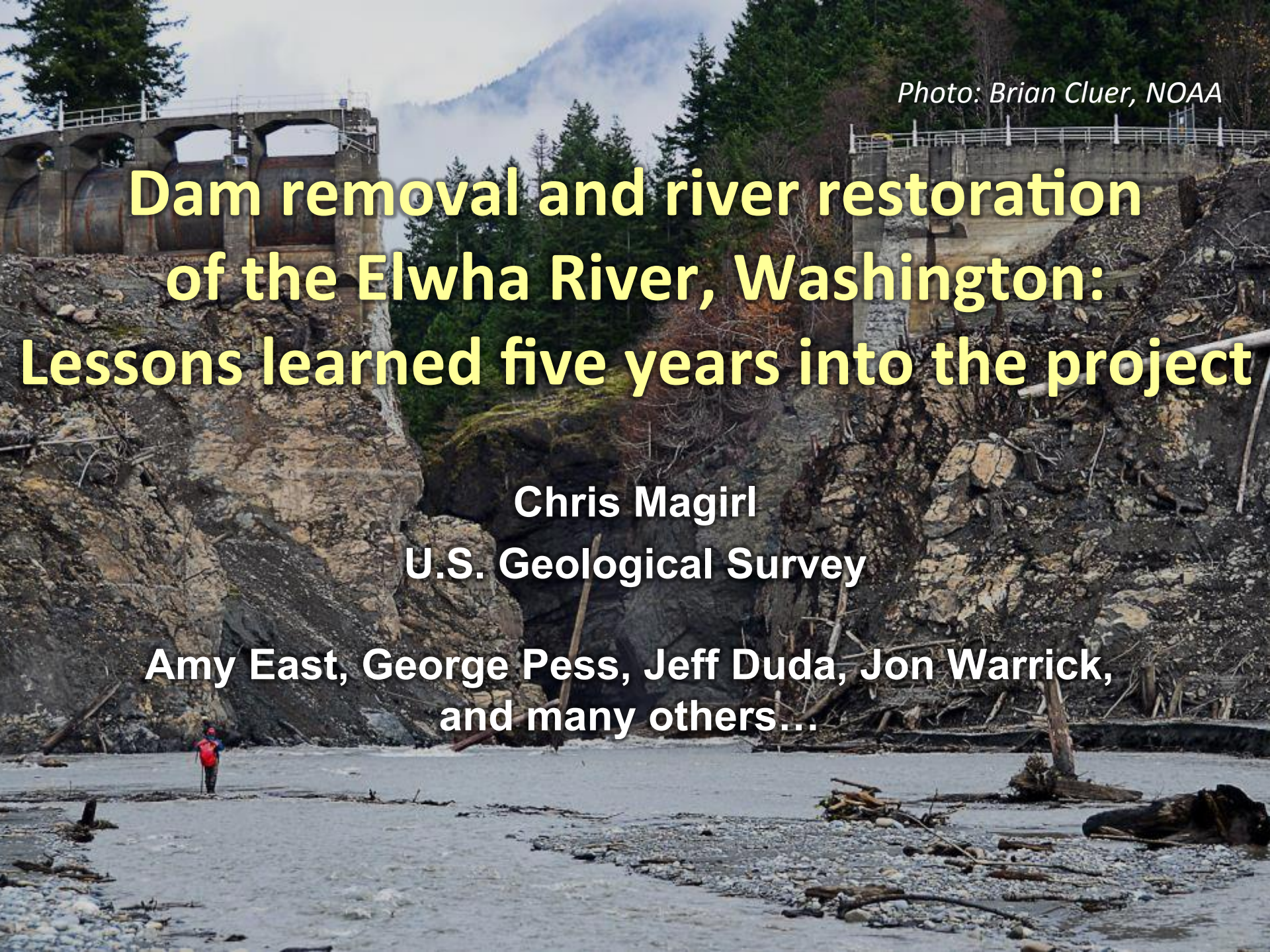

Photo: Brian Cluer, NOAA

Dam removal and river restoration of the Elwha River, Washington: Lessons learned five years into the project

Chris Magirl

U.S. Geological Survey

Amy East, George Pess, Jeff Duda, Jon Warrick, and many others…

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Co-Authors: (Physical Processes Papers)

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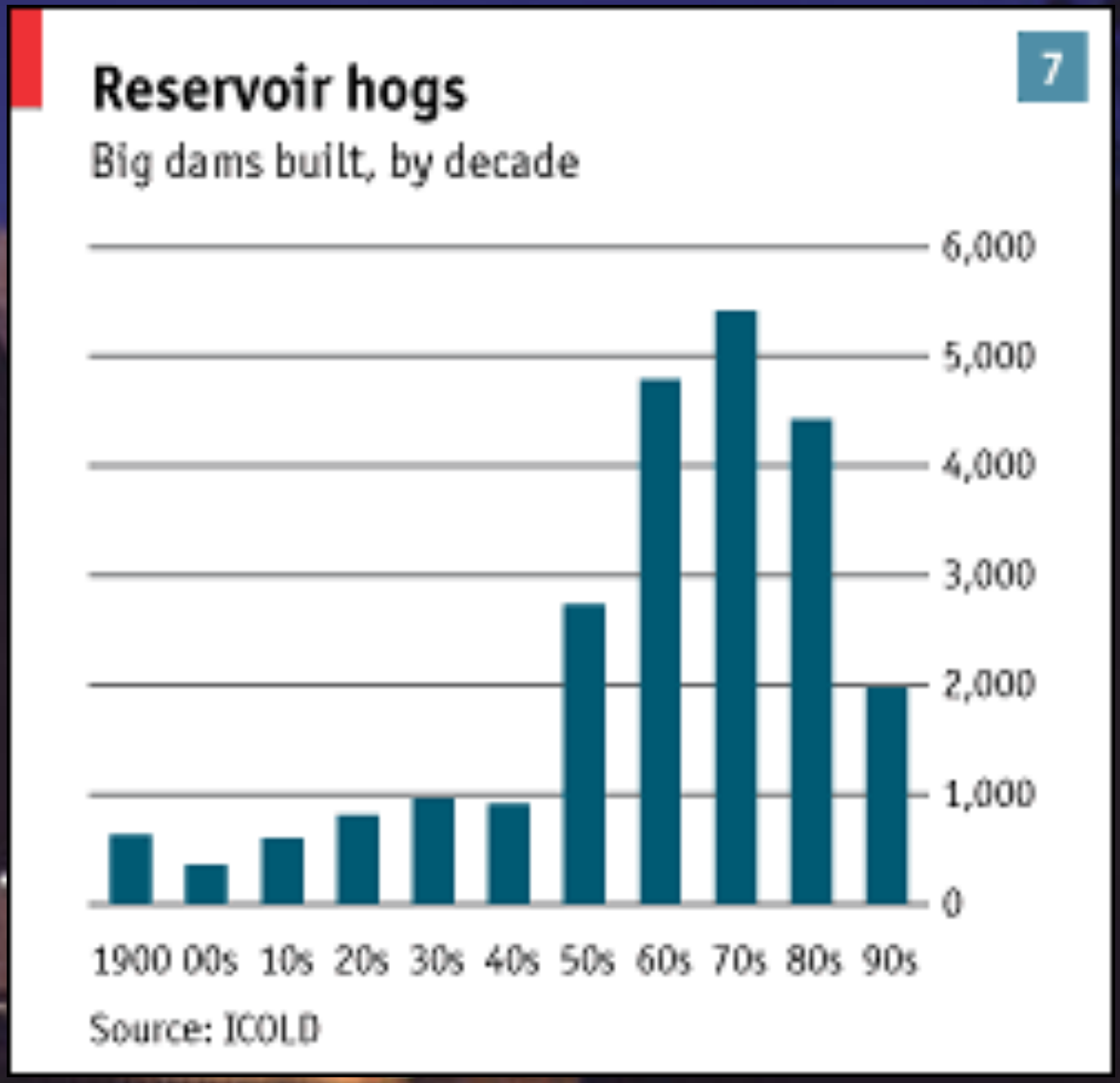

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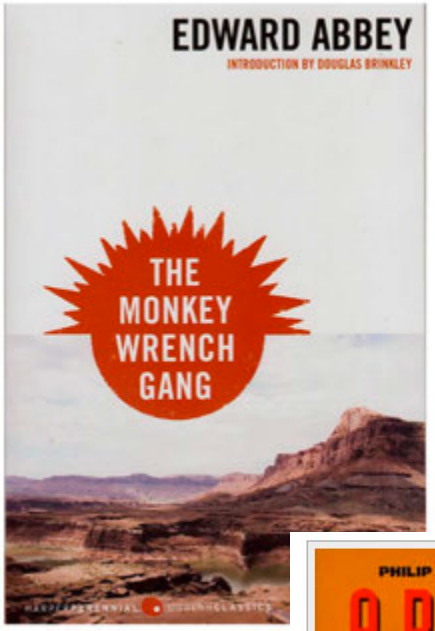
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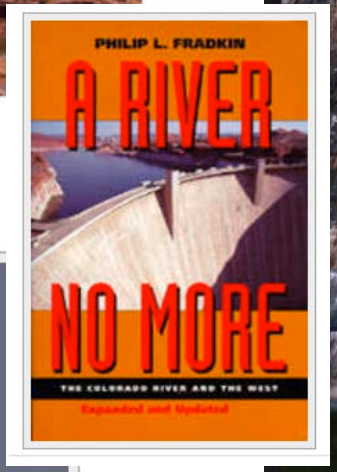
INTRODUCTION BY DOUGLAS BRINKLEY
THE MONKEY WRENCH GANG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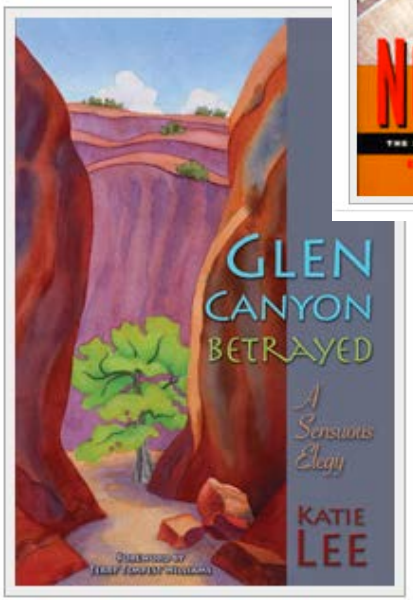
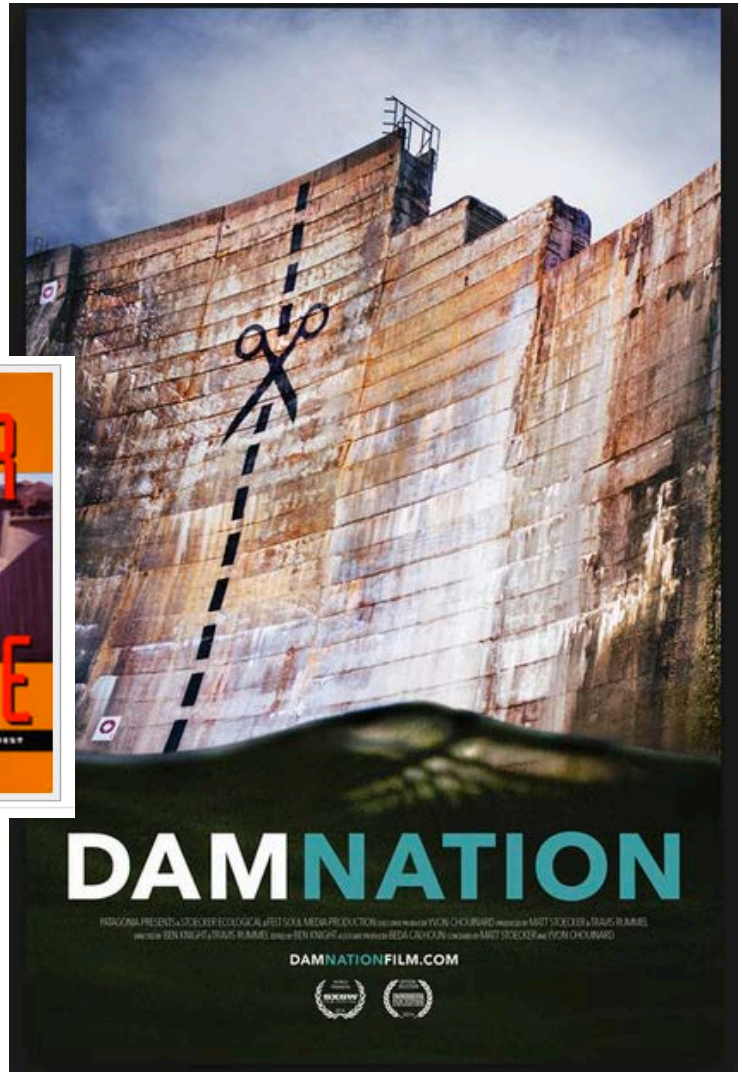
A RIVER
NO MORE
THE COLORADO RIVER AND THE WEST
Expanded and Updated


GLEN CANYON BETRAYED
A Sensuous Elegy
KATIE LEE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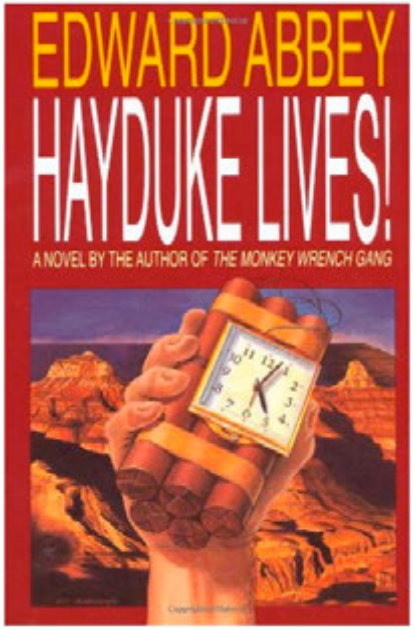
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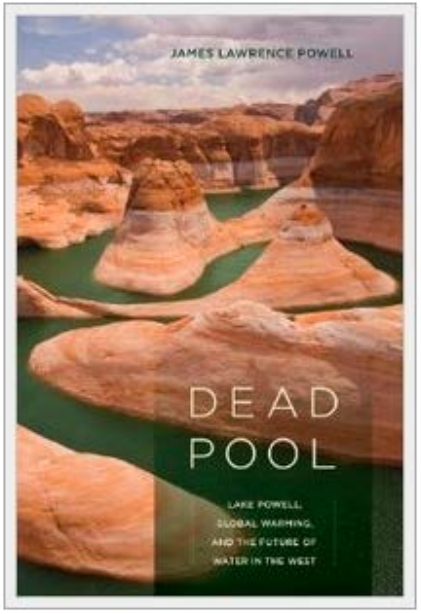
A NOVEL BY THE AUTHOR OF THE MONKEY WRENCH GANG


JAMES LAWRENCE POWELL
DEAD POOL
LAKE POWELL, GLOBAL WARMING, AND THE FUTURE OF WATER IN THE WEST


Lake Powell

INSIGHTS

Precision medicine comes to psychiatry p. 499

Secure sustainable seafood from developing countries p. 504

PERSPECTIVES

ECOLOGY

1000 dams down and counting

Dam removals are reconnecting rivers in the United States

By J. E. O'Connor,[1] J. J. Duda,[2] G. E. Grant[3]

Forty years ago, the demolition of large dams was mostly fiction, notably plotted in Edward Abbey's novel *The Monkey Wrench Gang*. Its 1975 publication roughly coincided with the end of large-dam construction in the United States. Since then, dams have been taken down in increasing numbers as they have filled with sediment, become unsafe or inefficient, or otherwise outlived their usefuln
A). Last year
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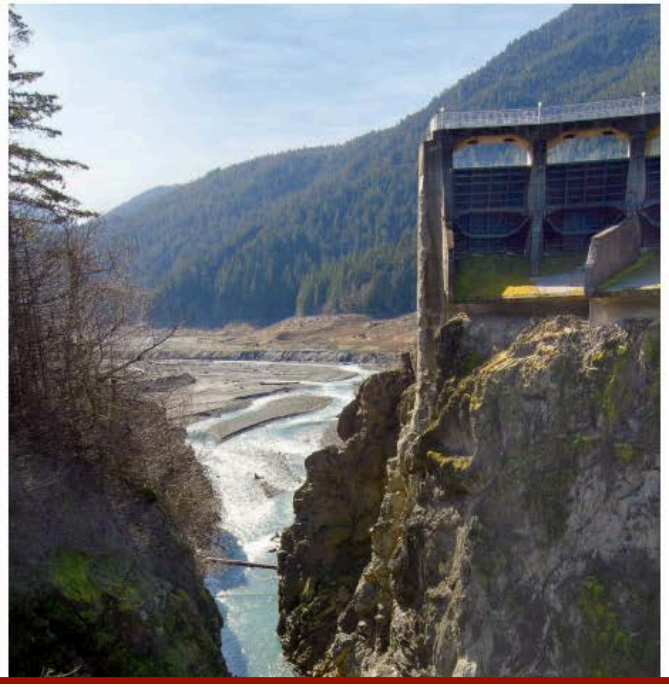
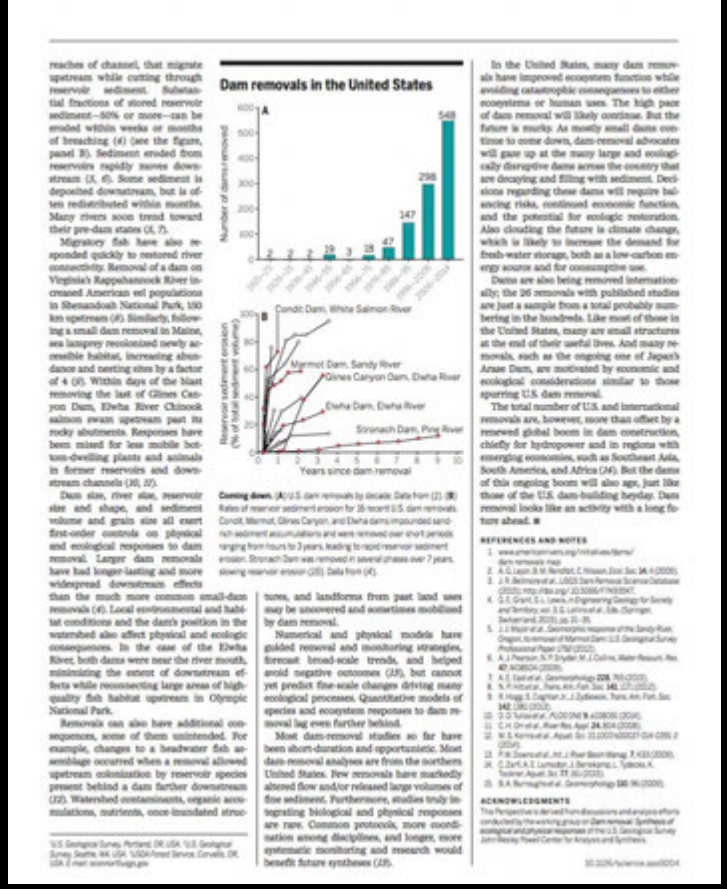
to river systems. Reservoir erosion commonly begins at knickpoints, or short steep



Goodbye to a large dam. Elwha River passing through the remains of Glines Canyon Dam on 21 September 2014. The former Lake Mills can be seen in the background.

Published by AAAS



reaches of channel, that migrate upstream while cutting through reservoir sediment. Substantial fractions of stored reservoir sediment—50% or more—can be eroded within weeks or months of breaching (4) (see the figure, panel B). Sediment eroded from reservoirs rapidly moves downstream (3, 4). Some sediment is deposited downstream, but is often redistributed within months. Many rivers soon trend toward their pre-dam states (3, 7).

Migratory fish have also responded quickly to restored river connectivity. Removal of a dam on Virginia's Rappahannock River increased American eel populations in Shenandoah National Park, 100 km upstream (16). Similarly, following a small dam removal in Maine, sea lamprey recolonized newly accessible habitat, increasing abundance and nesting sites by a factor of 4 (9). Within days of the blast removing the last of Glines Canyon Dam, Elwha River Chinook salmon swam upstream past its rocky abutments. Responses have been mixed for less mobile bottom-dwelling plants and animals in former reservoirs and downstream channels (10, 17).

Dam size, river size, reservoir size and shape, and sediment volume and grain size all exert first-order controls on physical and ecological responses to dam removal. Larger dam removals have had longer-lasting and more widespread downstream effects than the much more common small-dam removals (4). Local environmental and habitat conditions and the dam's position in the watershed also affect physical and ecologic consequences. In the case of the Elwha River, both dams were near the river mouth, minimizing the extent of downstream effects while reconnecting large areas of high-quality fish habitat upstream in Olympic National Park.

Removals can also have additional consequences, some of them unintended. For example, changes to a headwater fish assemblage occurred when a removal allowed upstream colonization by reservoir species present behind a dam farther downstream (12). Watershed contaminants, organic accumulations, nutrients, once-inundated structures, and landforms from past land uses may be uncovered and sometimes mobilized by dam removal.

Numerical and physical models have guided removal and monitoring strategies, forecast broad-scale trends, and helped avoid negative outcomes (18), but cannot yet predict fine-scale changes driving many ecological processes. Quantitative models of species and ecosystem responses to dam removal lag even further behind.

Most dam-removal studies so far have been short-duration and opportunistic. Most dam-removal analyses are from the northern United States. Few removals have markedly altered flow and/or released large volumes of fine sediment. Furthermore, studies truly integrating biological and physical responses are rare. Common protocols, more coordination among disciplines, and longer, more systematic monitoring and research would benefit future syntheses (19).

Dam removals in the United States

Coming down. (**A**) U.S. dam removals by decade. Data from (*1*). (**B**) Rates of reservoir sediment erosion for 16 recent U.S. dam removals. Condit, Marmot, Glines Canyon, and Elwha dams impounded sand-rich sediment accumulations and were removed over short periods ranging from hours to 3 years, leading to rapid reservoir sediment erosion. Stronach Dam was removed in several phases over 7 years, slowing reservoir erosion (*18*). Data from (*4*).

In the United States, many dam removals have improved ecosystem function while avoiding catastrophic consequences to either ecosystems or human uses. The high pace of dam removal will likely continue. But the future is murky. As mostly small dams continue to come down, dam-removal advocates will gaze up at the many large and ecologically damaging dams across the country that are decaying and filling with sediment. Decisions regarding these dams will require balancing risks, continued economic function, and the potential for ecologic restoration. Also clouding the future is climate change, which is likely to increase the demand for fresh-water storage, both as a low-carbon energy source and for consumptive use.

Dams are also being removed internationally; the 26 removals with published studies are just a sample from a total probably numbering in the hundreds. Like most of those in the United States, many are small structures at the end of their useful lives. And many removals, such as the ongoing one of Japan's Arase Dam, are motivated by economic and ecological considerations similar to those spurring U.S. dam removal.

The total number of U.S. and international removals are, however, more than offset by a renewed global boom in dam construction, chiefly for hydropower and in regions with emerging economies, such as Southeast Asia, South America, and Africa (*16*). But the dams of this ongoing boom will also age, just like those of the U.S. dam-building heyday. Dam removal looks like an activity with a long future ahead. ■

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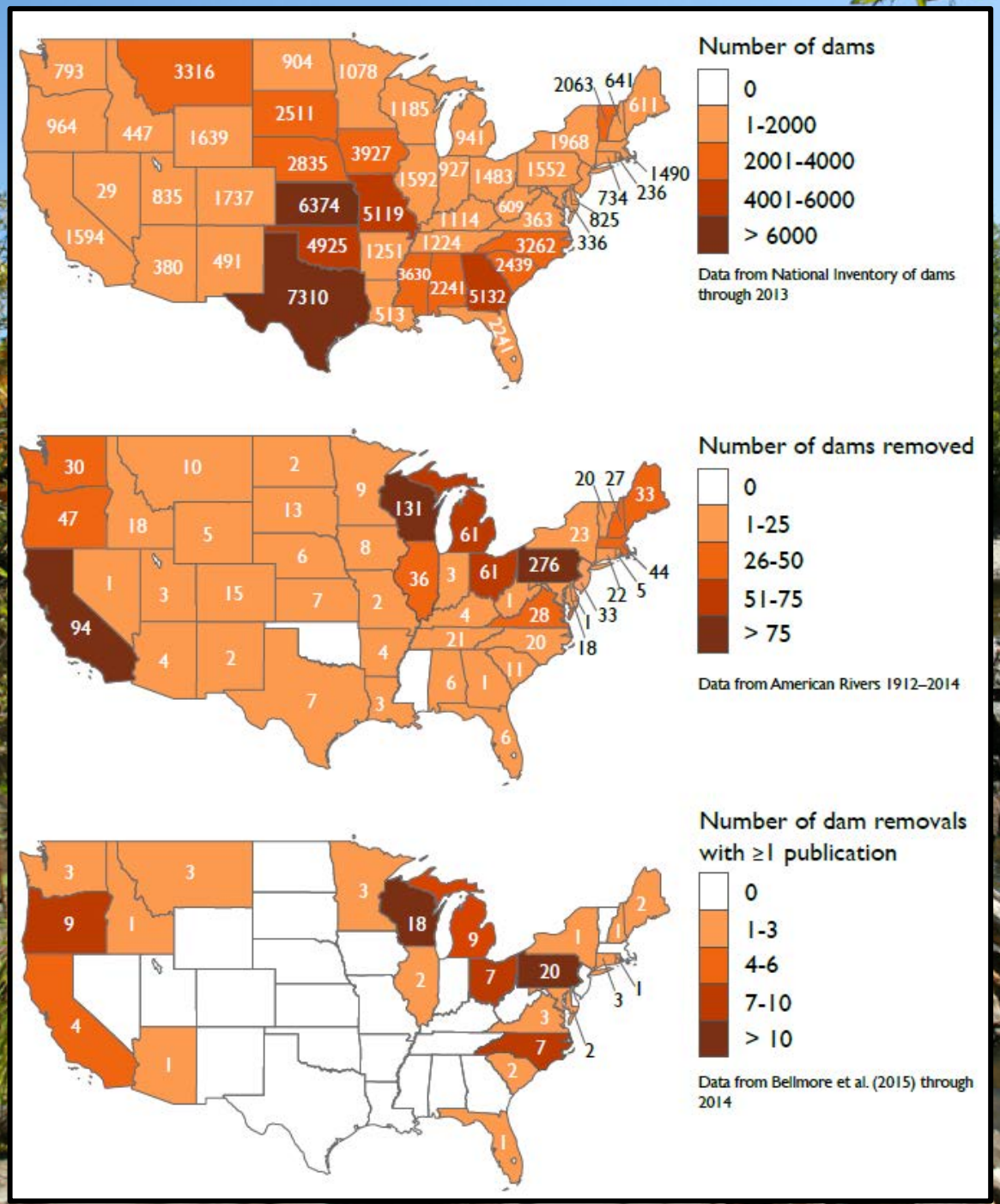
10.1126/science.aaa9204

A major finding is that rivers are resilient, with many responding quickly to dam removal. Most river channels stabilize within months or years, not decades (*4*),

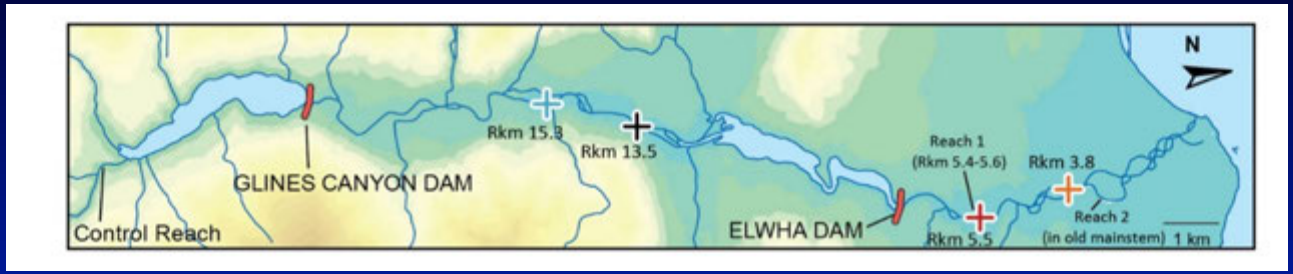
O'Connor et al. (2015) Science



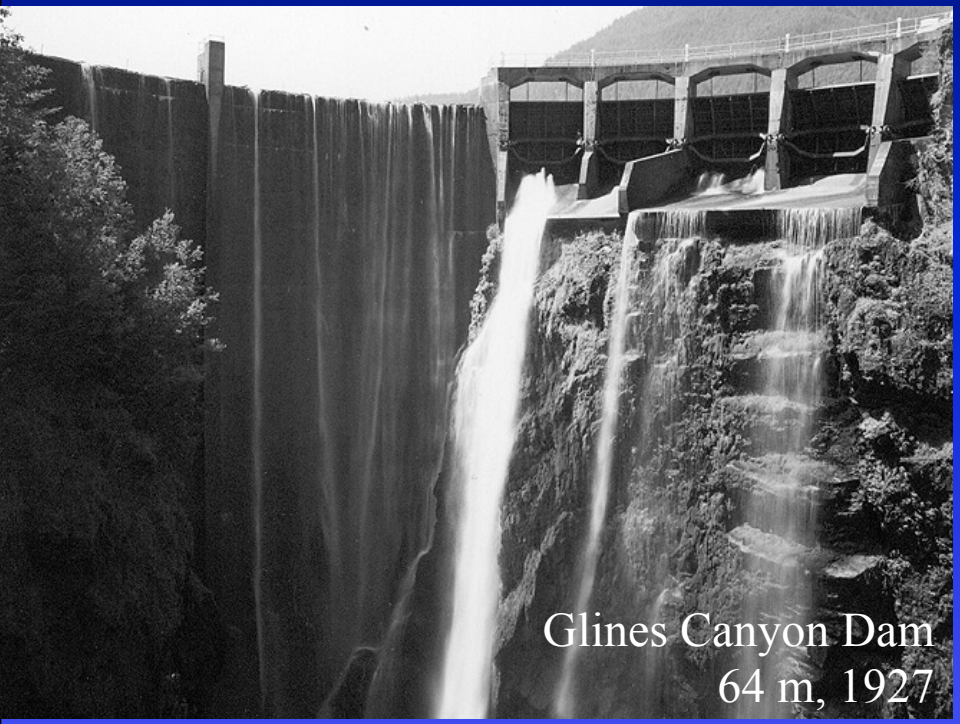
Bellmore et al. (2016)

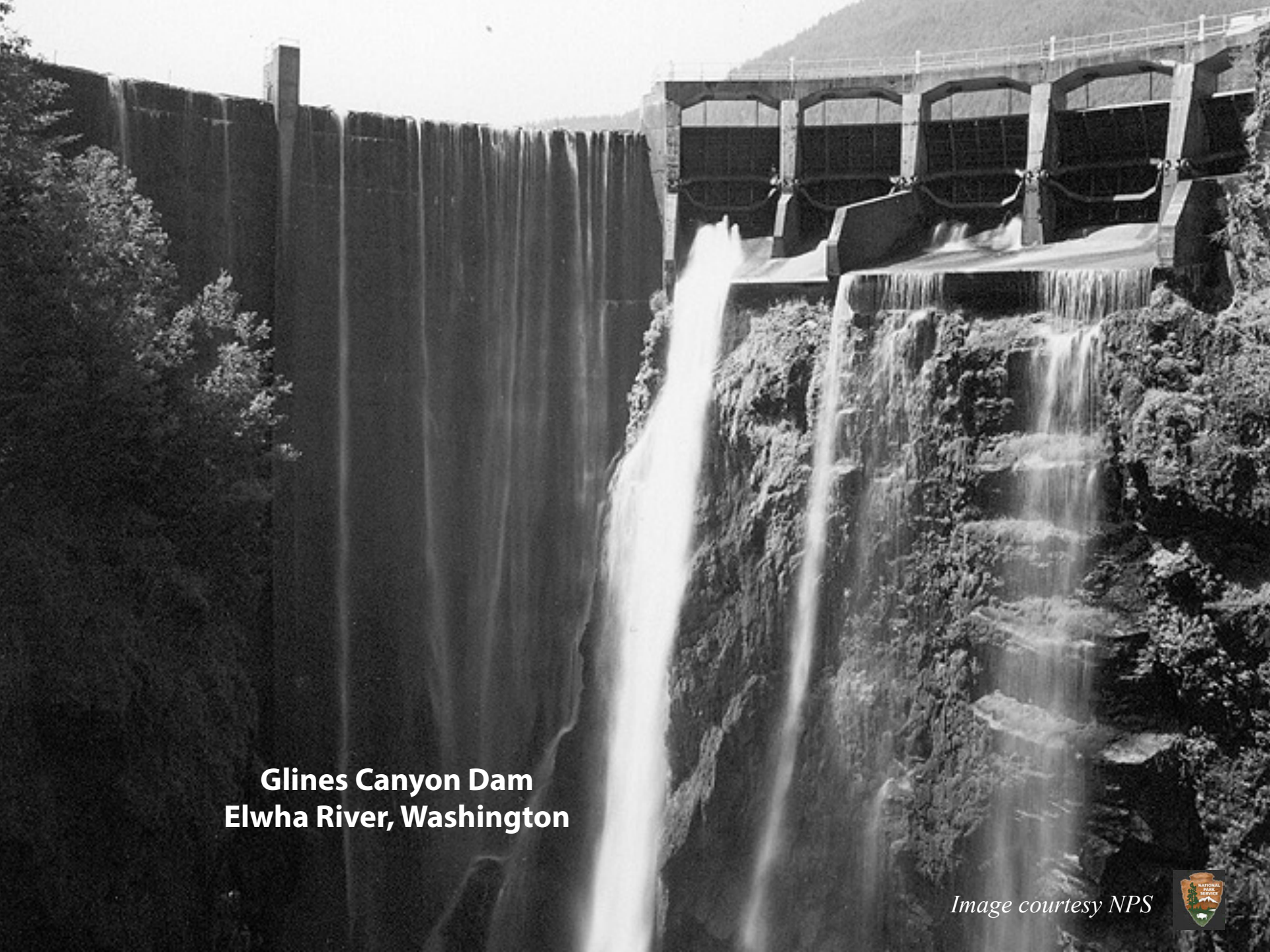
Photo courtesy NOAA


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth



Images courtesy NPS





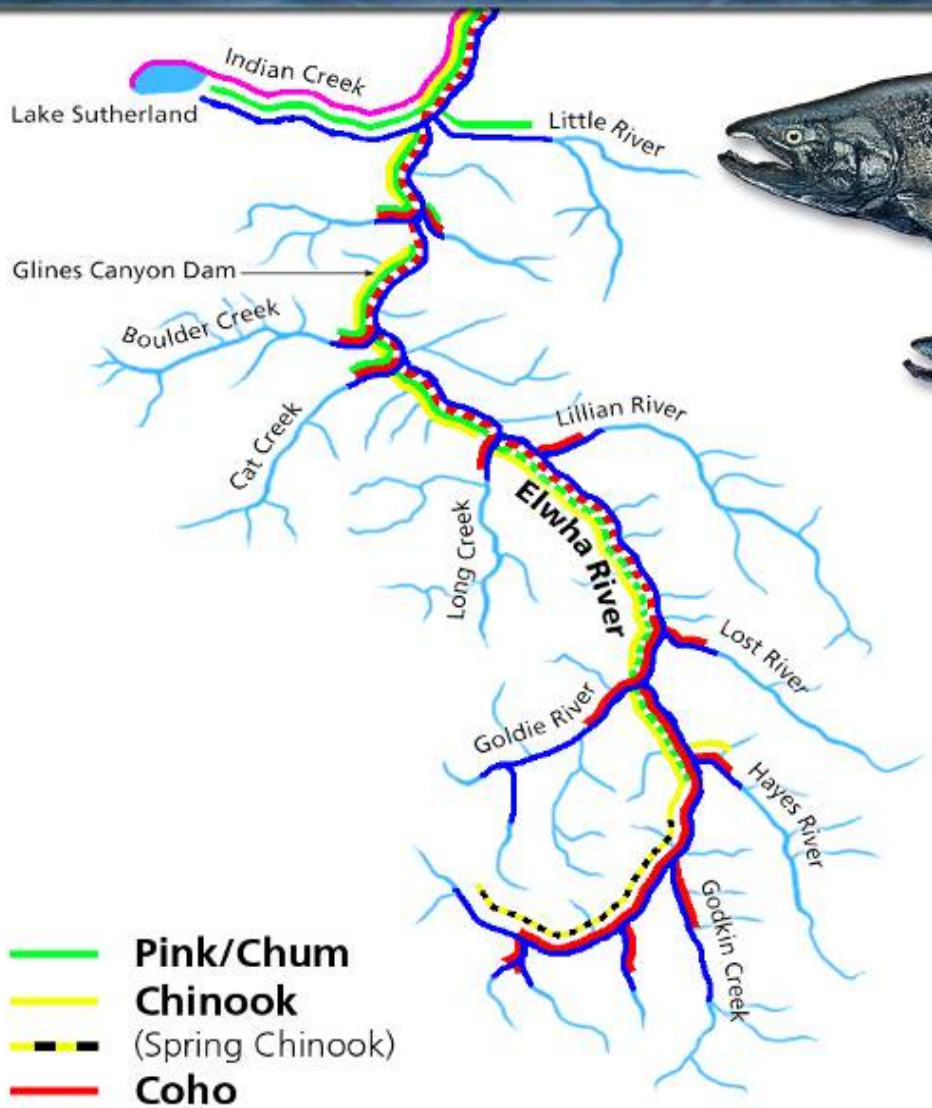
Glines Canyon Dam
Elwha River, Washington

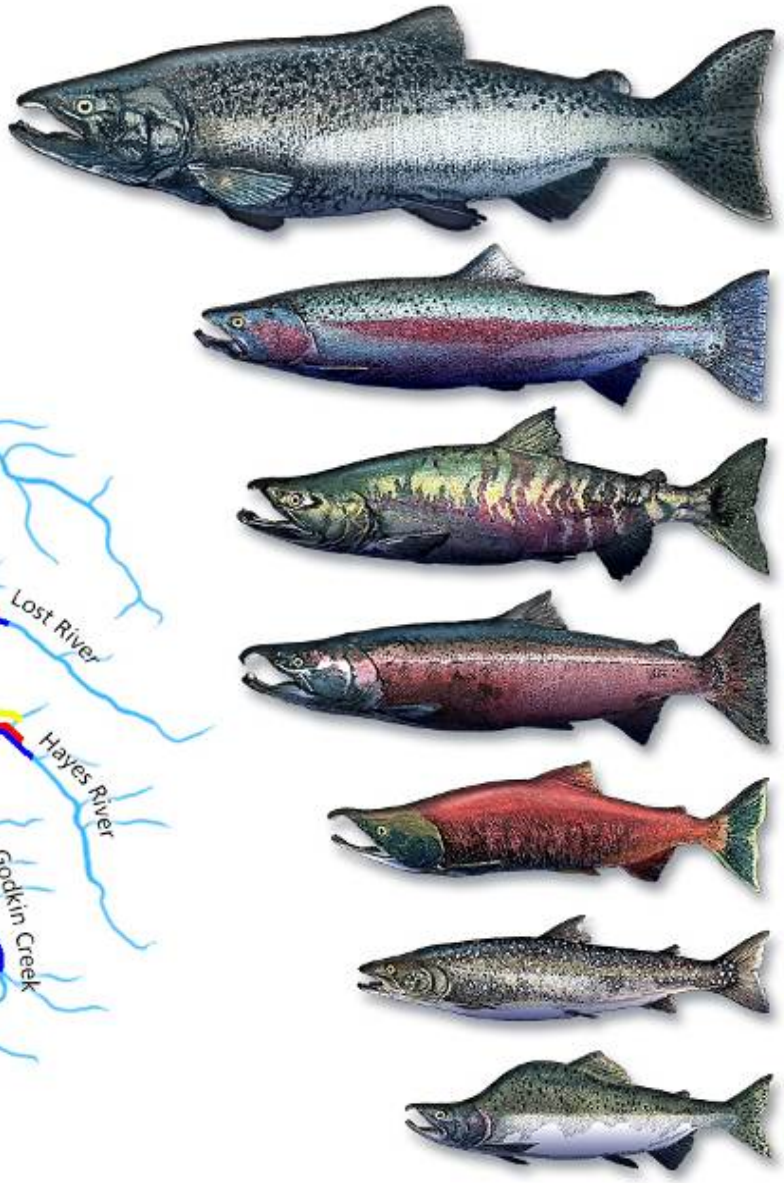
Image courtesy NPS

Photo credit:
John Gussman

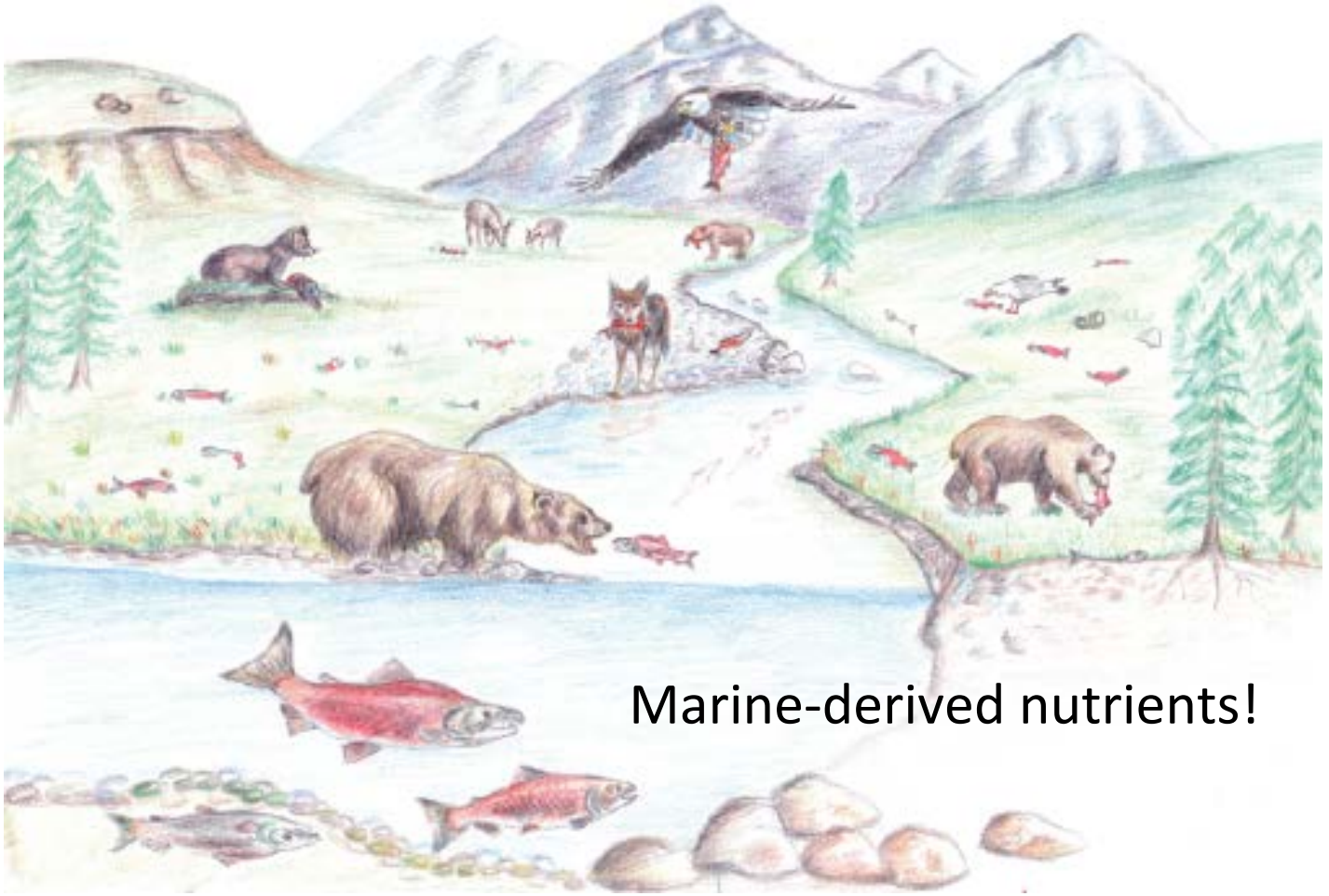

Photo by John McMillan

Potential Range Map for the Seven Elwha Salmonids





How do ecosystems respond?



Drawing by Yiwei Wang

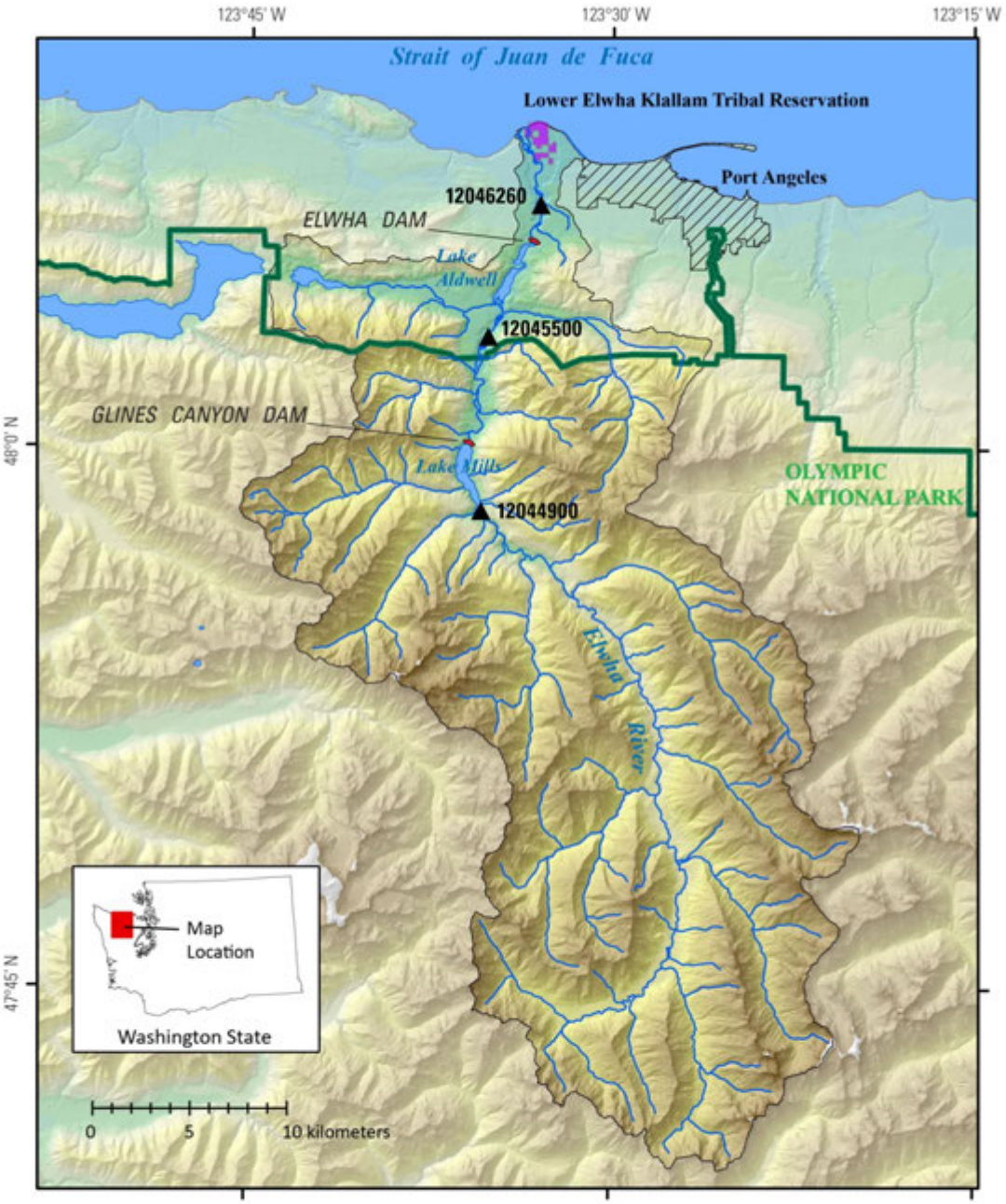
Terrestrial linkages
Marine-derived nutrients in the Elwha foodweb

The case of the American dipper (*Cinclus mexicanus*)

Photo by Chris Tonra

Photo by John McMillan

Elwha River watershed



Historically, the Elwha River supported large, healthy fish before the dams were constructed.
Washington Historical Society

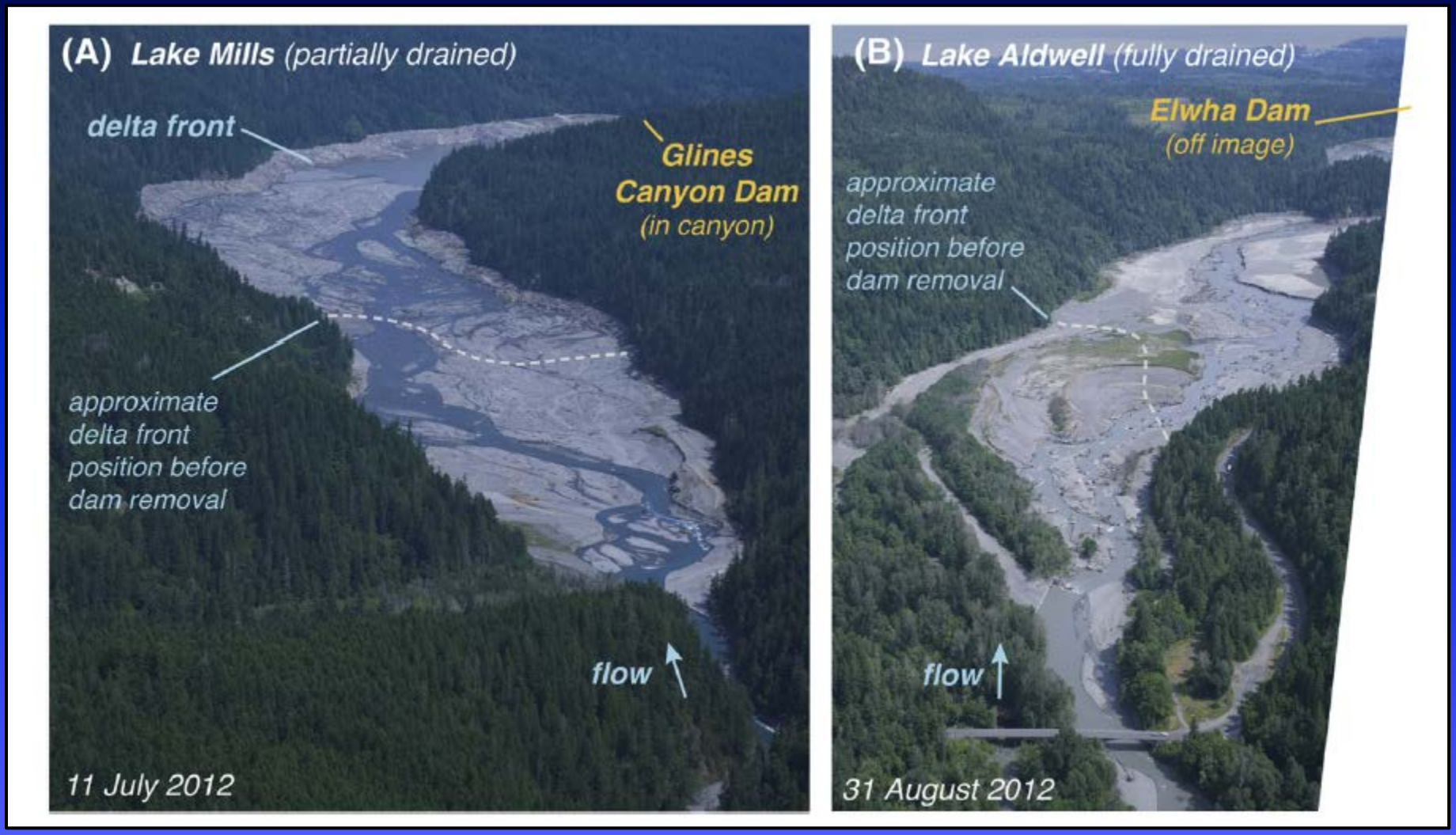
Elwha River Ecosystem and Fisheries Restoration Act

"…for the removal of the dams and full restoration of the Elwha River ecosystem and native anadromous fisheries."

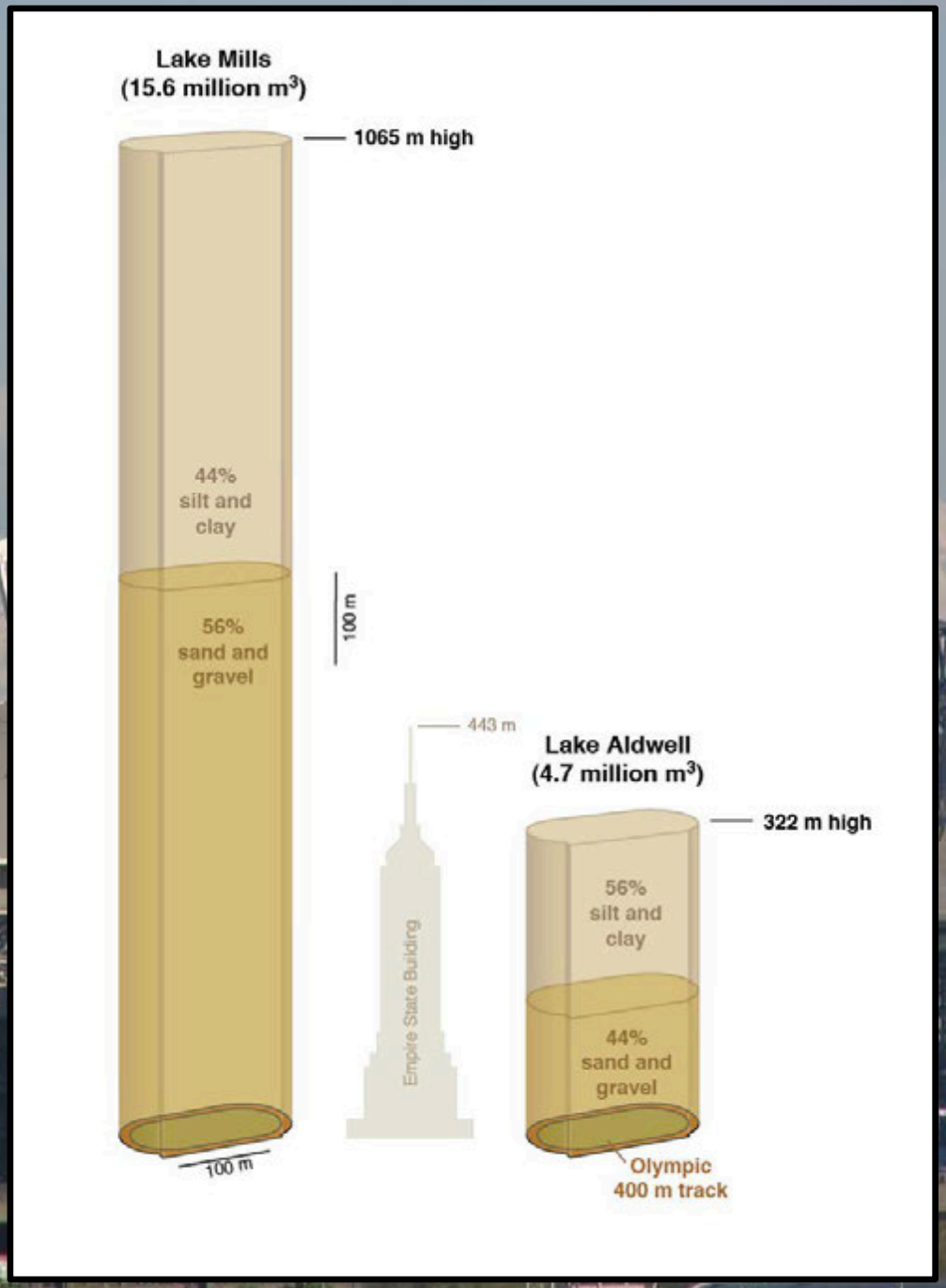
102nd Congress of the U.S.A.
January 3, 1992


Photo courtesy of Josh Chenoweth

21 Million Tonnes of Trapped Sediment

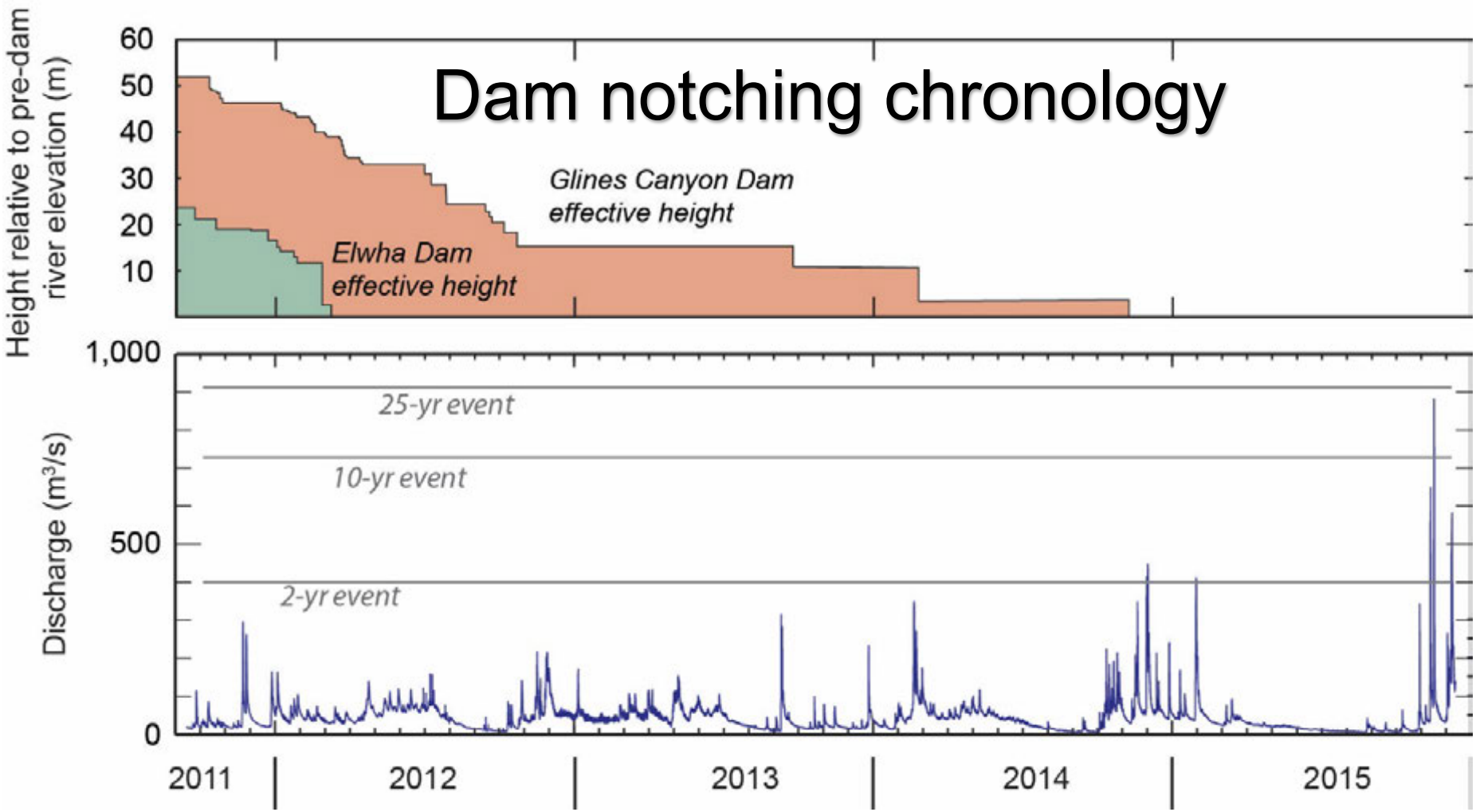


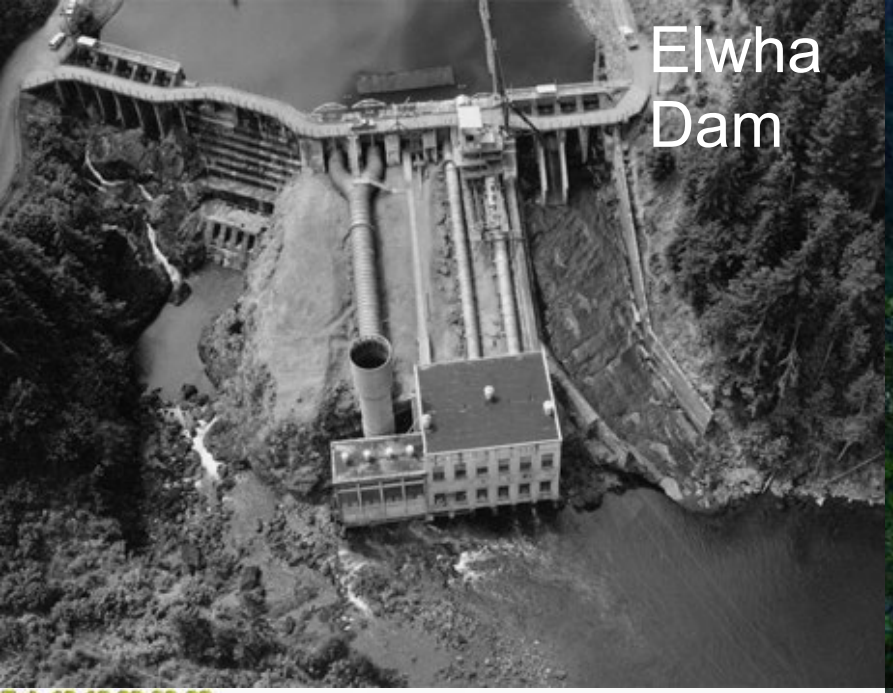
From Warrick et al. (2015)



from Warrick et al. (2015)

Dam notching chronology




Elwha
Dam


September 2011

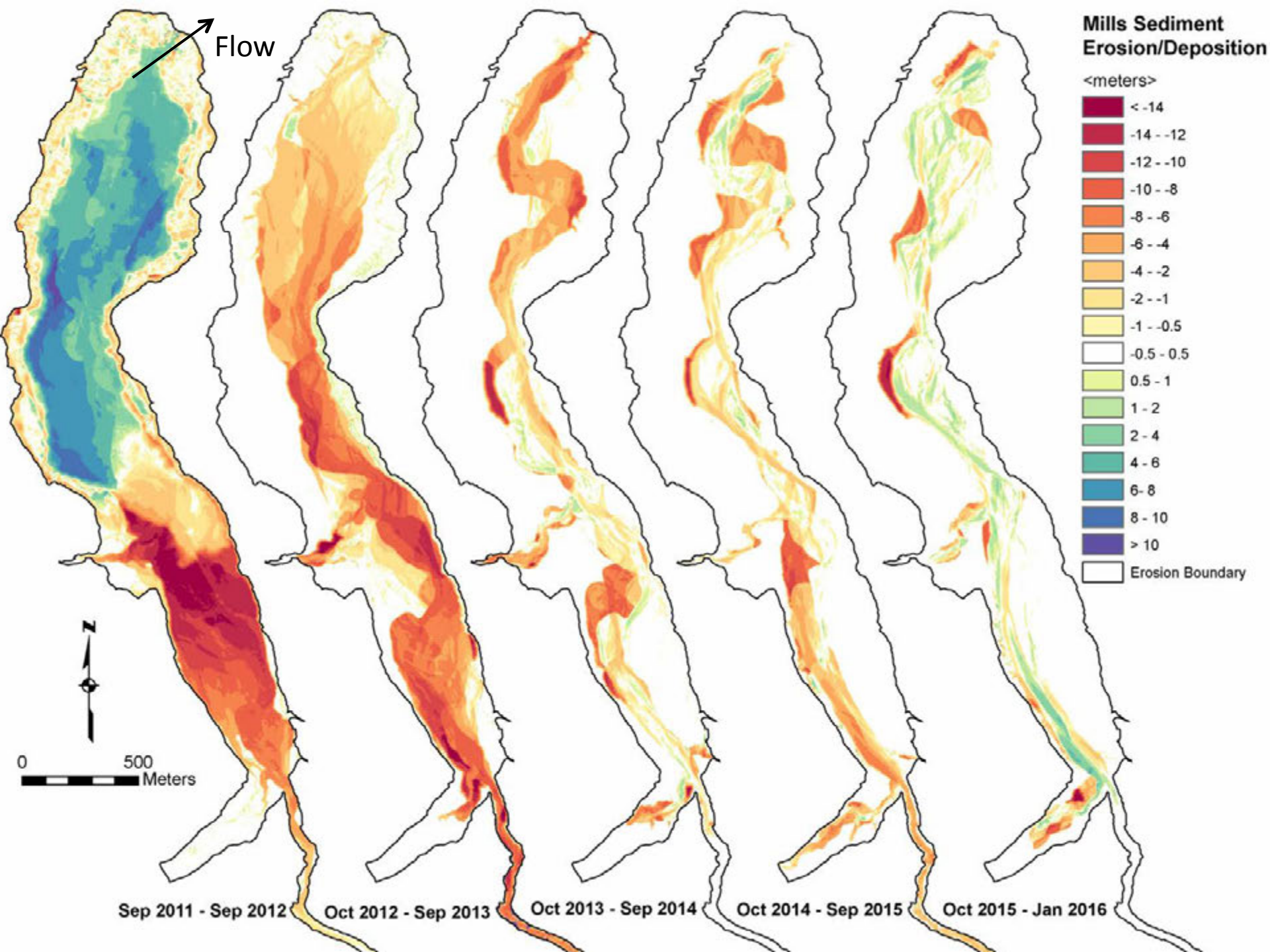

Feb 13 12 09:33:38
February 2012


August
2012


May 12 14 08:32:59

Blasting at Glines Canyon Dam

John Gussman


Flow
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< -14
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-2 - -1
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2 - 4
4 - 6
6- 8
8 - 10
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Erosion Boundary
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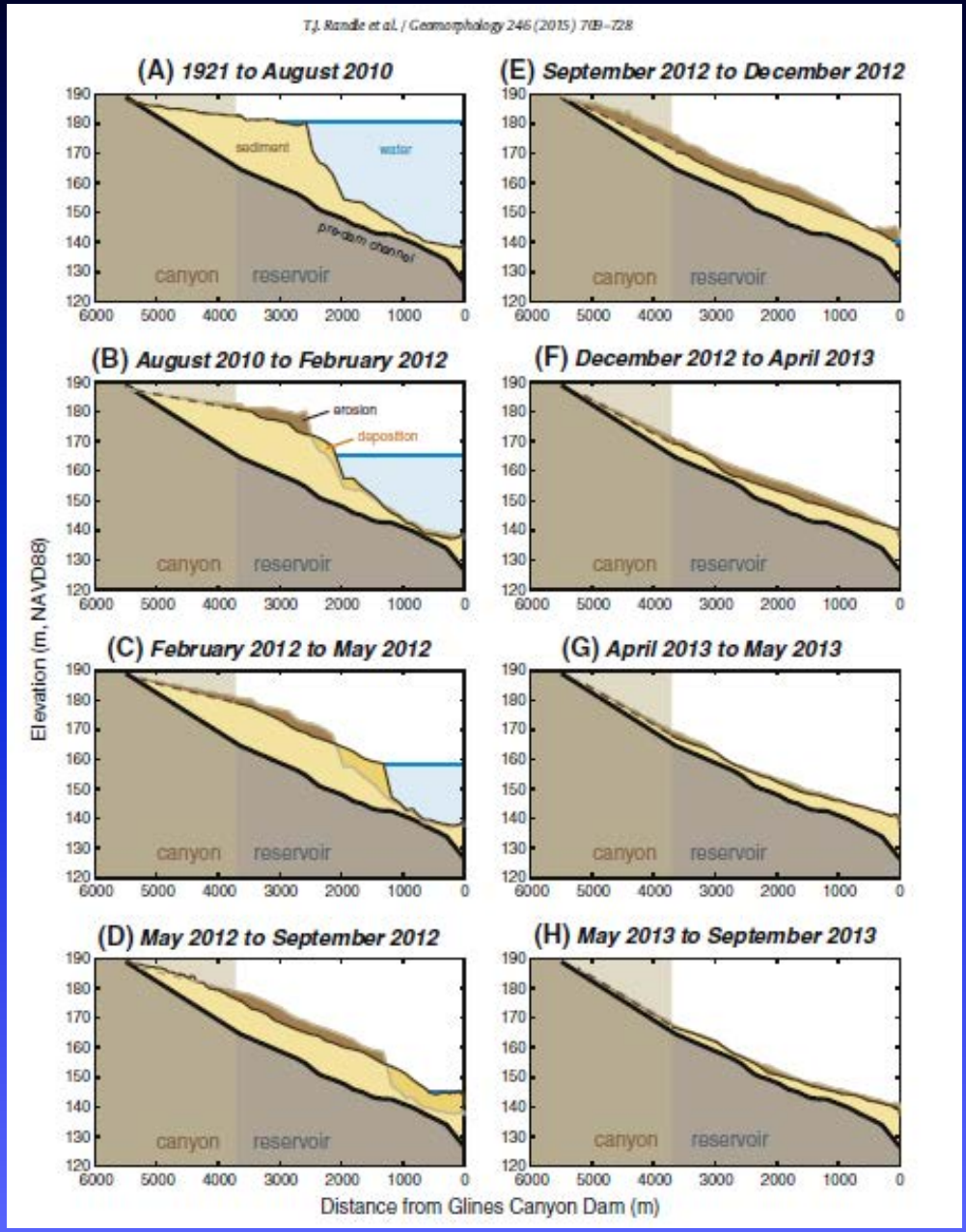
Oct 2012 - Sep 2013
Oct 2013 - Sep 2014
Oct 2014 - Sep 2015
Oct 2015 - Jan 2016

Reservoir Delta Evolution



From Randle et al. (2015)

Elwha River Restoration Project

ELWHA RIVER RESTORATION

Project Location:

Approximately 7 miles west of Port Angeles on the Olympic Peninsula in Washington State

Elwha Watershed

Aerial Photos:

Lake Aldwell / Elwha Dam

Lake Mills / Glines Canyon Dam

Glines Canyon Dam

SlideShows: HTML5 ~ Silverlight ~ Mobile

Former Lake Mills

SlideShows: HTML5 ~ Silverlight ~ Mobile

Lower Lake Mills

SlideShows: HTML5 ~ Silverlight ~ Mobile

Lake Mills Delta

SlideShows: HTML5 ~ Silverlight ~ Mobile

Lower Lake Aldwell

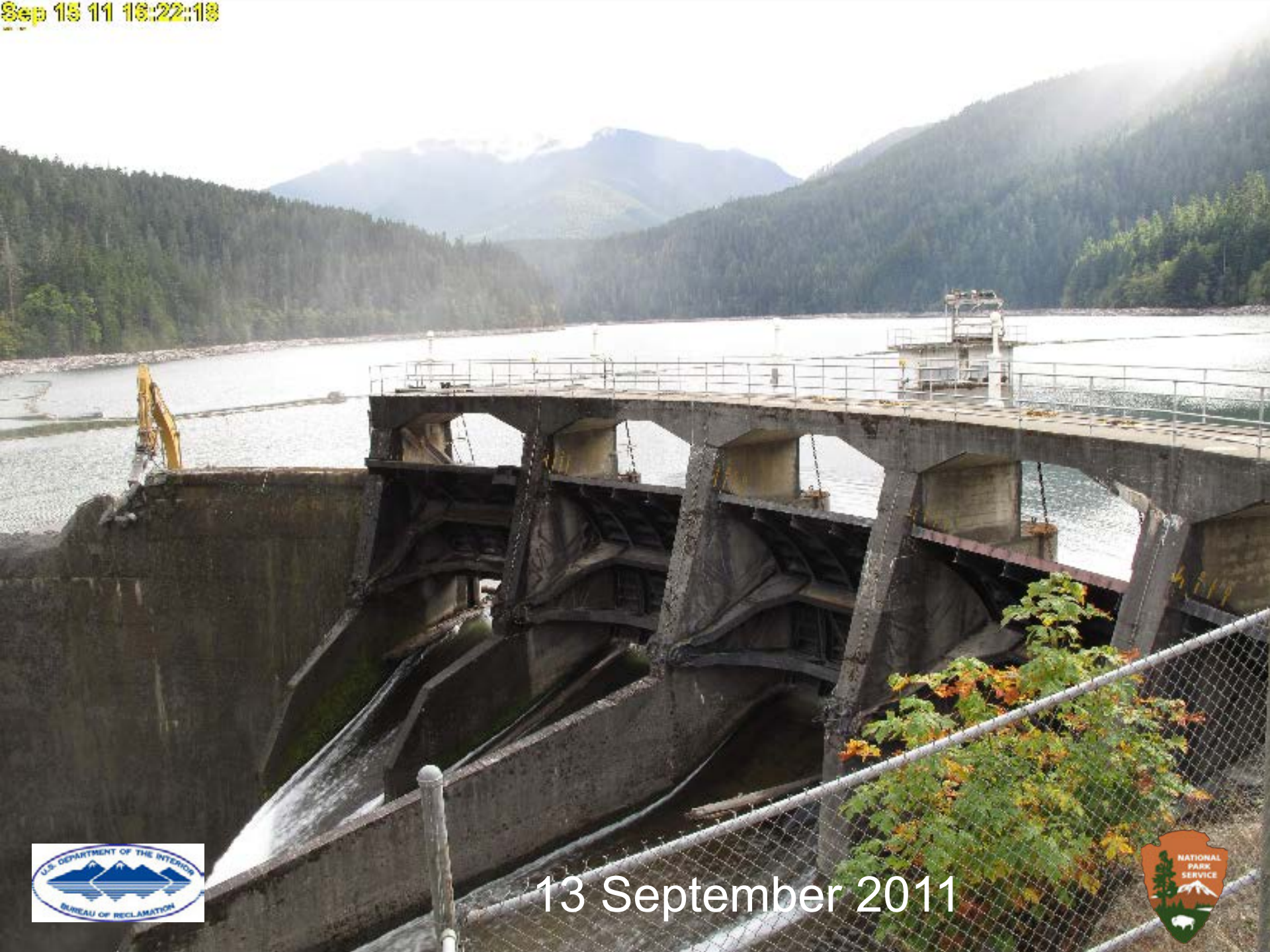
SlideShows: HTML5 ~ Silverlight ~ Mobile

Lake Aldwell Delta

SlideShows: HTML5 ~ Silverlight ~ Mobile

Elwha Dam (Finished)

Elwha Dam Updated Photo


Sep 15 11 16:22:18
13 September 2011


Apr 21 12 15:33:02
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
NATIONAL PARK SERVICE
21 April 2012


Aug 19 12 15:33:18
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
19 August 2012
NATIONAL PARK SERVICE


Sep 23 12 14:03:20
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
23 September 2012
NATIONAL PARK SERVICE


Oct 06 12 11:33:17
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
NATIONAL PARK SERVICE
06 October 2012


Dec 03 12 12:32:54
Drawdown 129 feet
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
03 December 2012
NATIONAL PARK SERVICE


Feb 09 13 12:32:29
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BUREAU OF RECLAMATION
09 February 2013
NATIONAL PARK SERVICE


Aug 08 13 14:33:01
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BUREAU OF RECLAMATION
NATIONAL PARK SERVICE
08 August 2013


Aug 18 14 13:32:28
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
NATIONAL PARK SERVICE
18 August 2014


Dec 07 14 12:33:59
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BUREAU OF RECLAMATION
07 December 2014
NATIONAL PARK SERVICE


Dec 19 14 12:32:23
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
19 December 2014
NATIONAL PARK SERVICE


Jan 03 15 12:02:42
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
03 January 2015
NATIONAL PARK SERVICE


Mar 10 15 12:03:12
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
10 March 2015
NATIONAL PARK SERVICE


Oct 05 16 15:42:16
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
5 Oct 2016
NATIONAL PARK SERVICE


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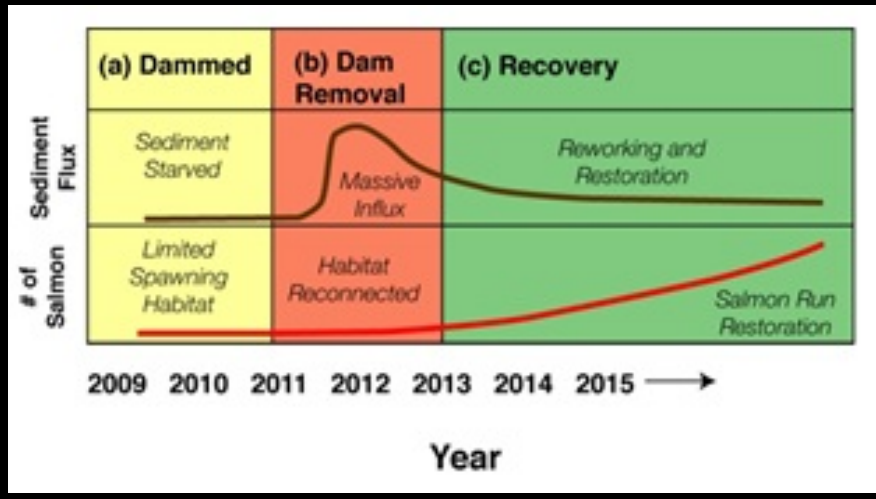
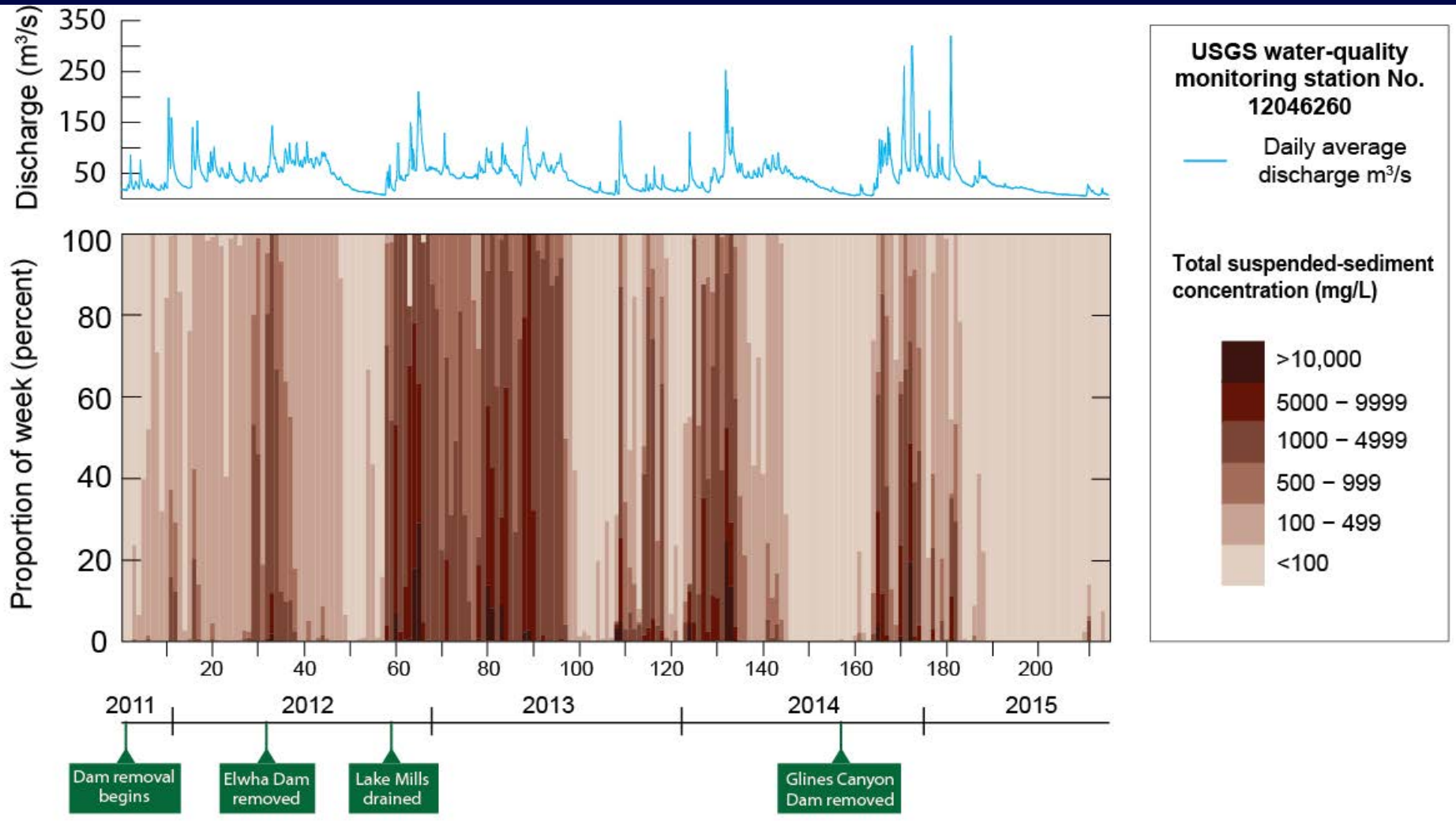
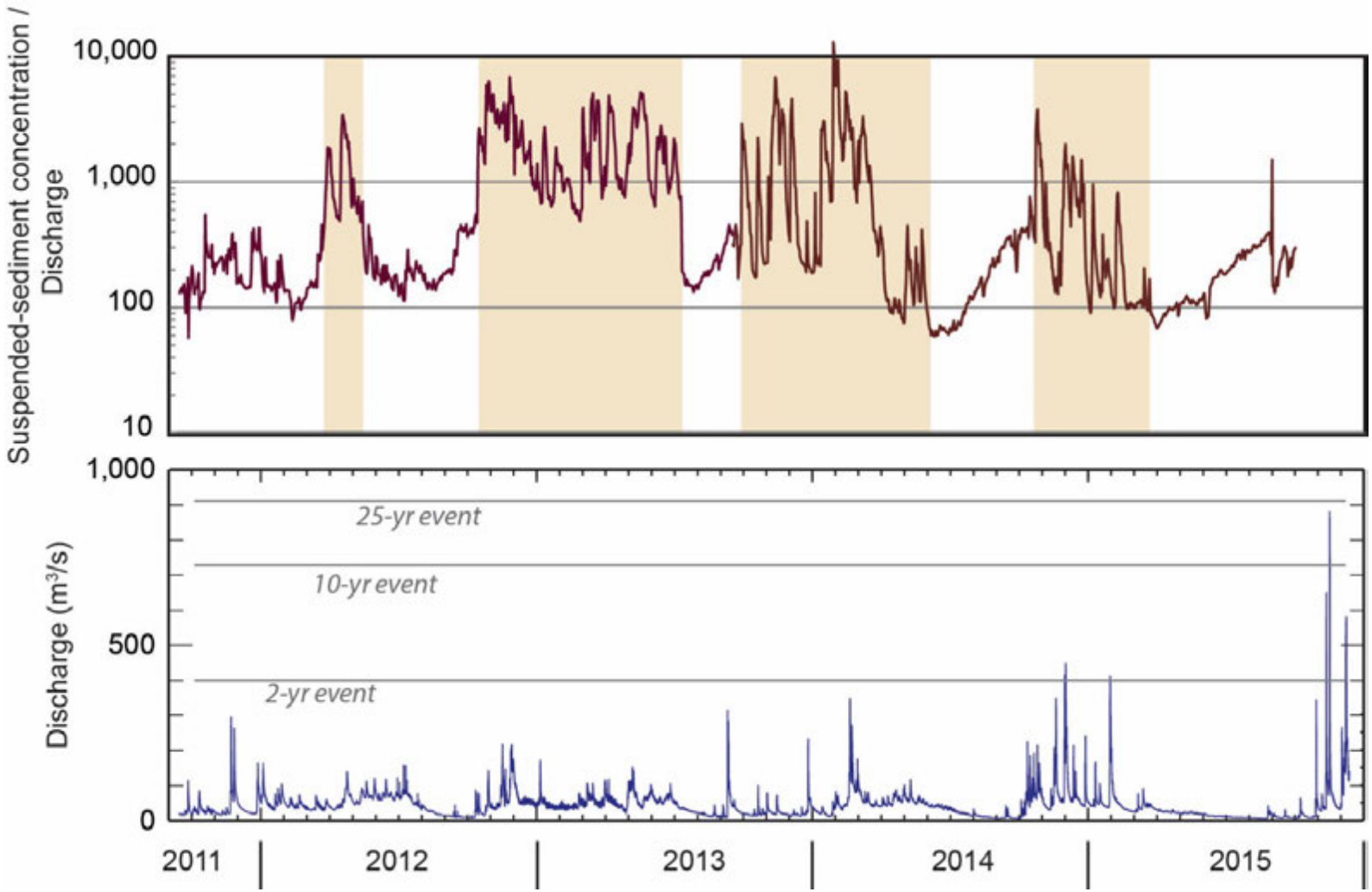
Science and Monitoring Questions:

(a)What will happen to the fish?
(b)What will happen to the ecosystems?
(c)What will happen to the sediment?

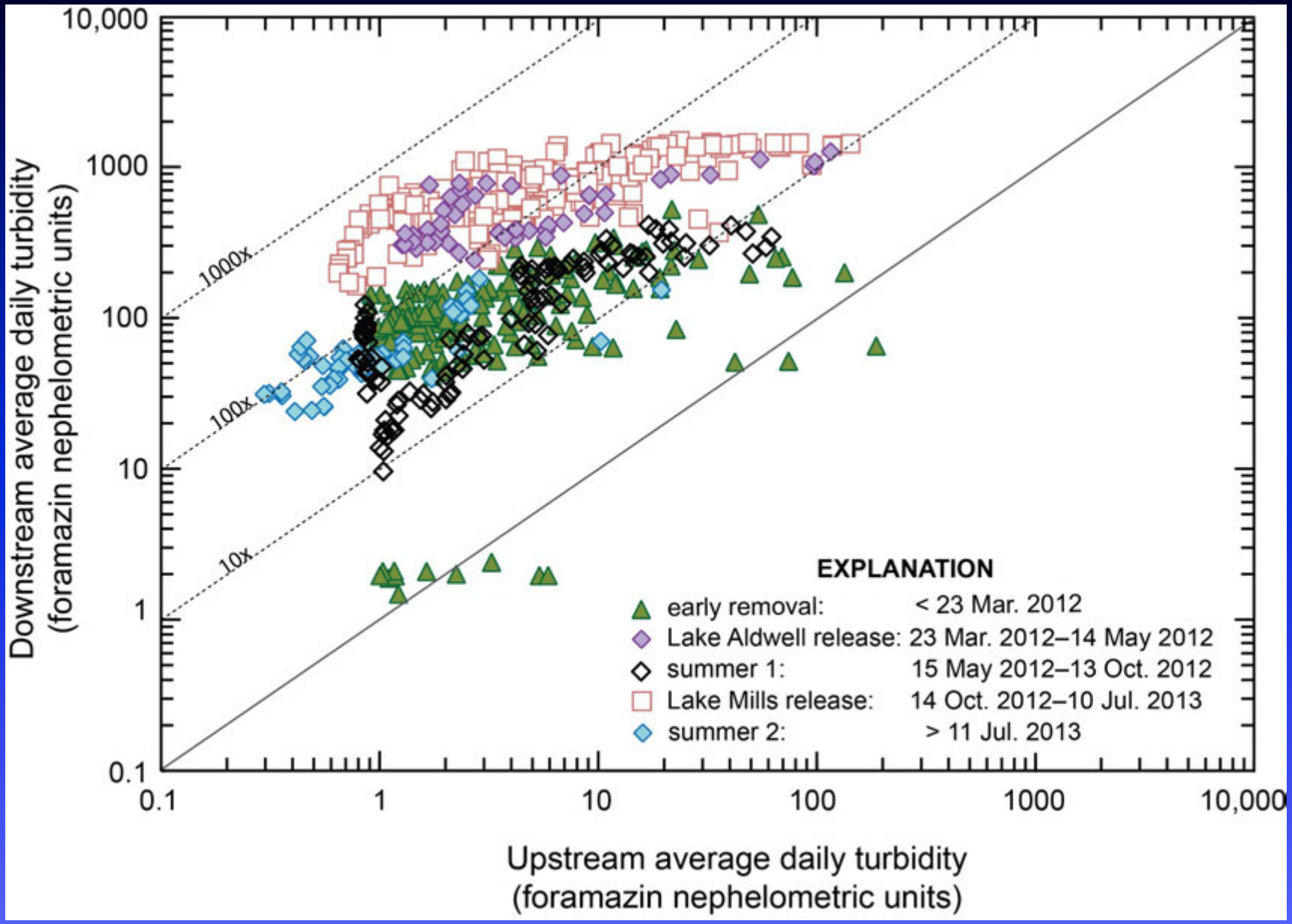


SSC bins by week




Suspended-sediment concentration / Discharge
10,000
1,000
100
10
1,000
500
0
Discharge (m³/s)
25-yr event
10-yr event
2-yr event
2011
2012
2013
2014
2015

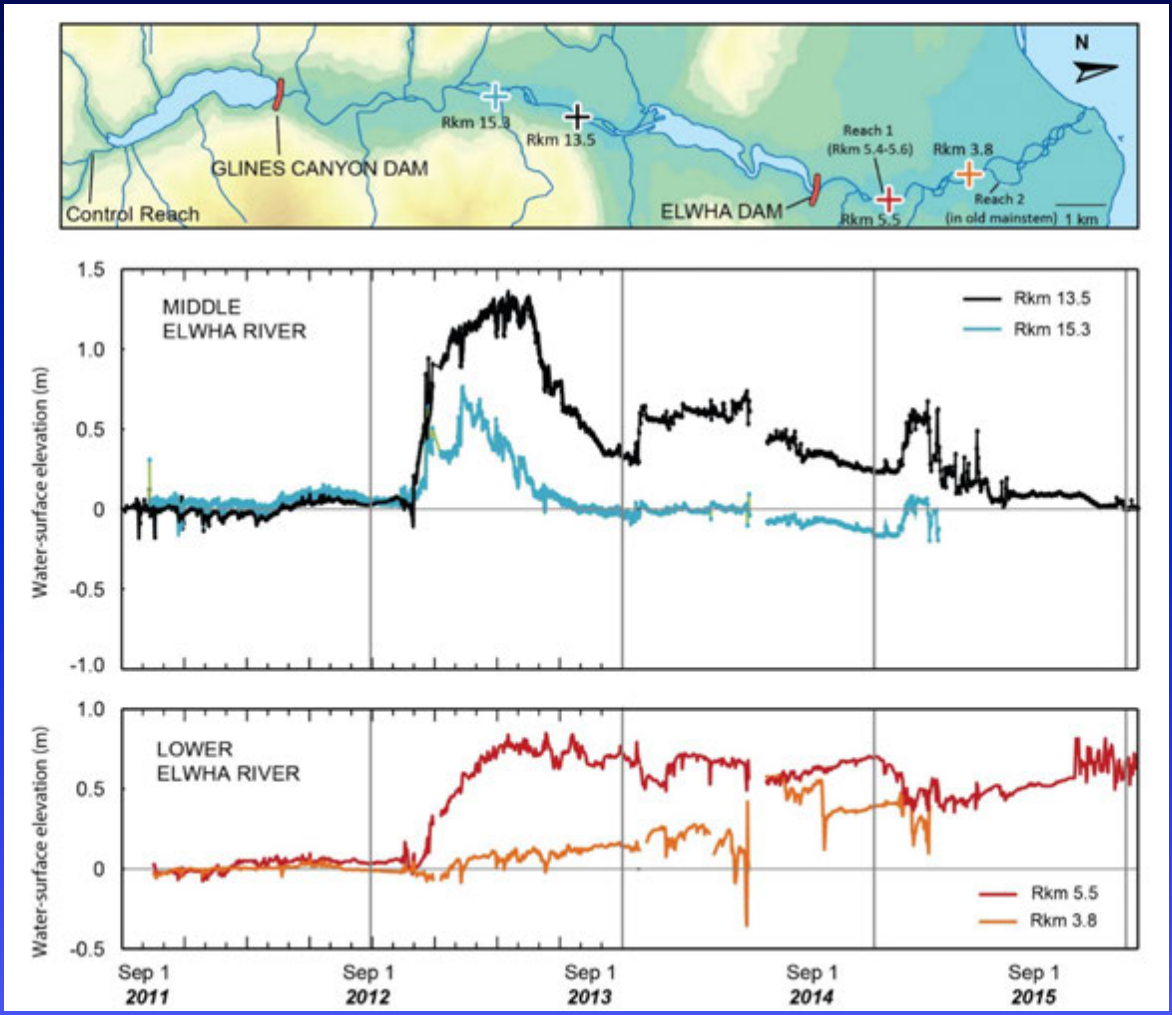
Comparative Turbidity

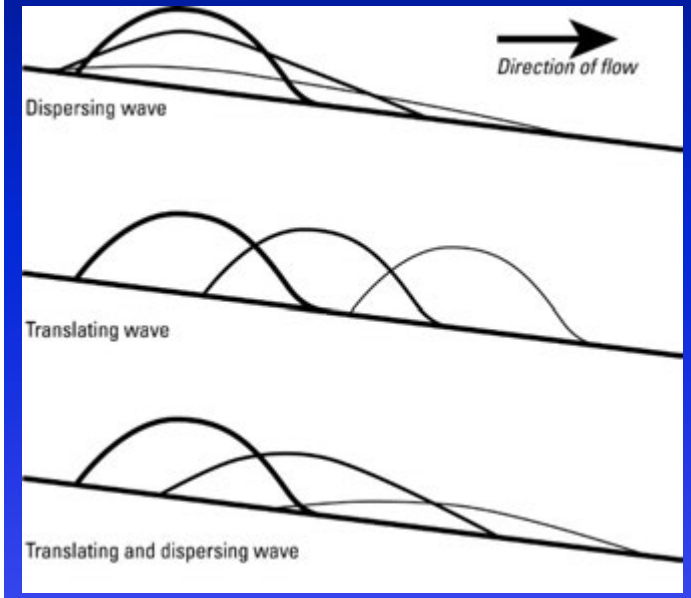


from Magirl et al. (2015)

Sediment Wave Dynamics

from East et al. (2015)





from Lisle (2008)

Longitudinal Profile

Typical Shallow Pool

USGS Gage
Deep Pool

Before Dam Removal
Water Stage

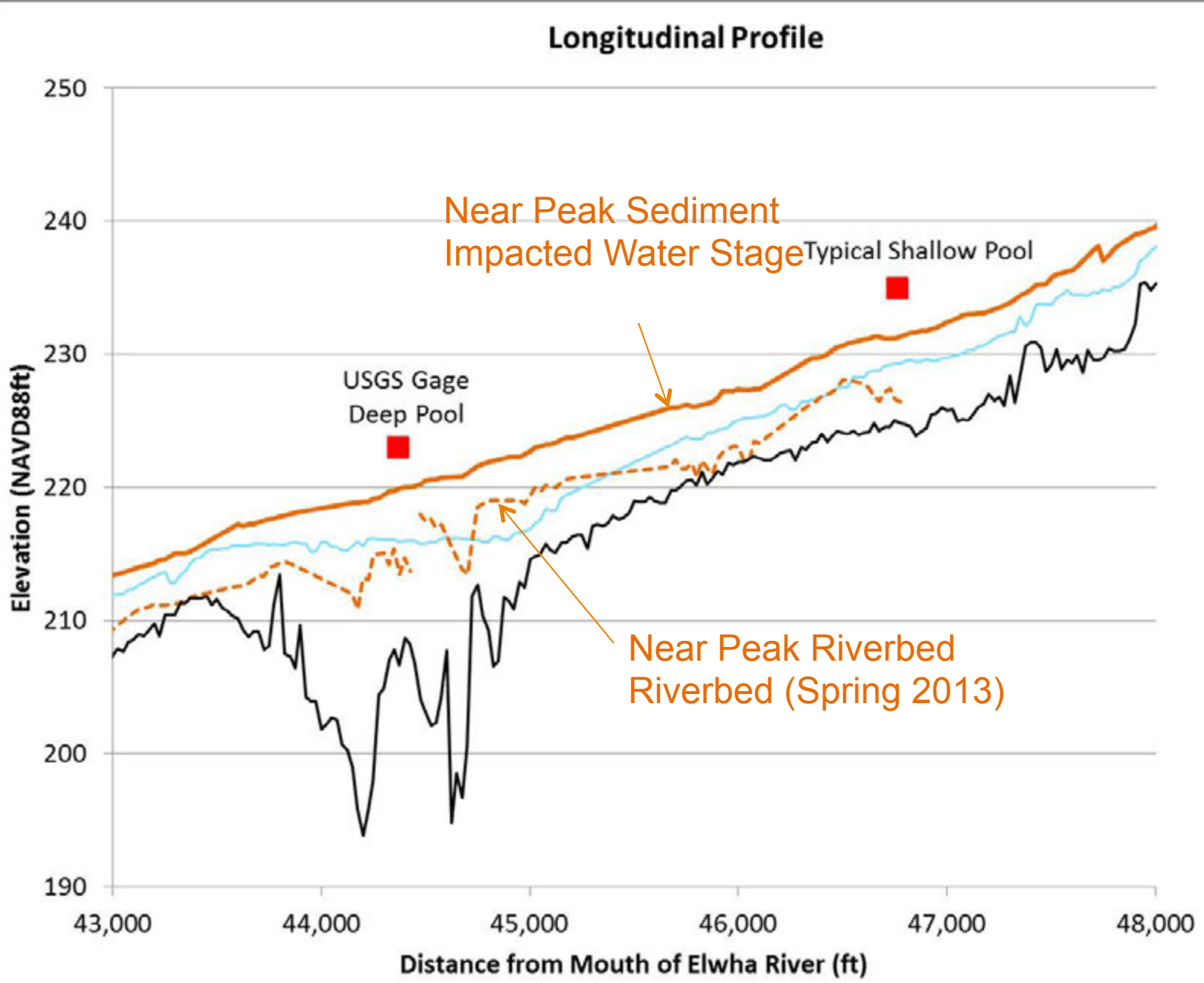
Before Dam Removal
Riverbed

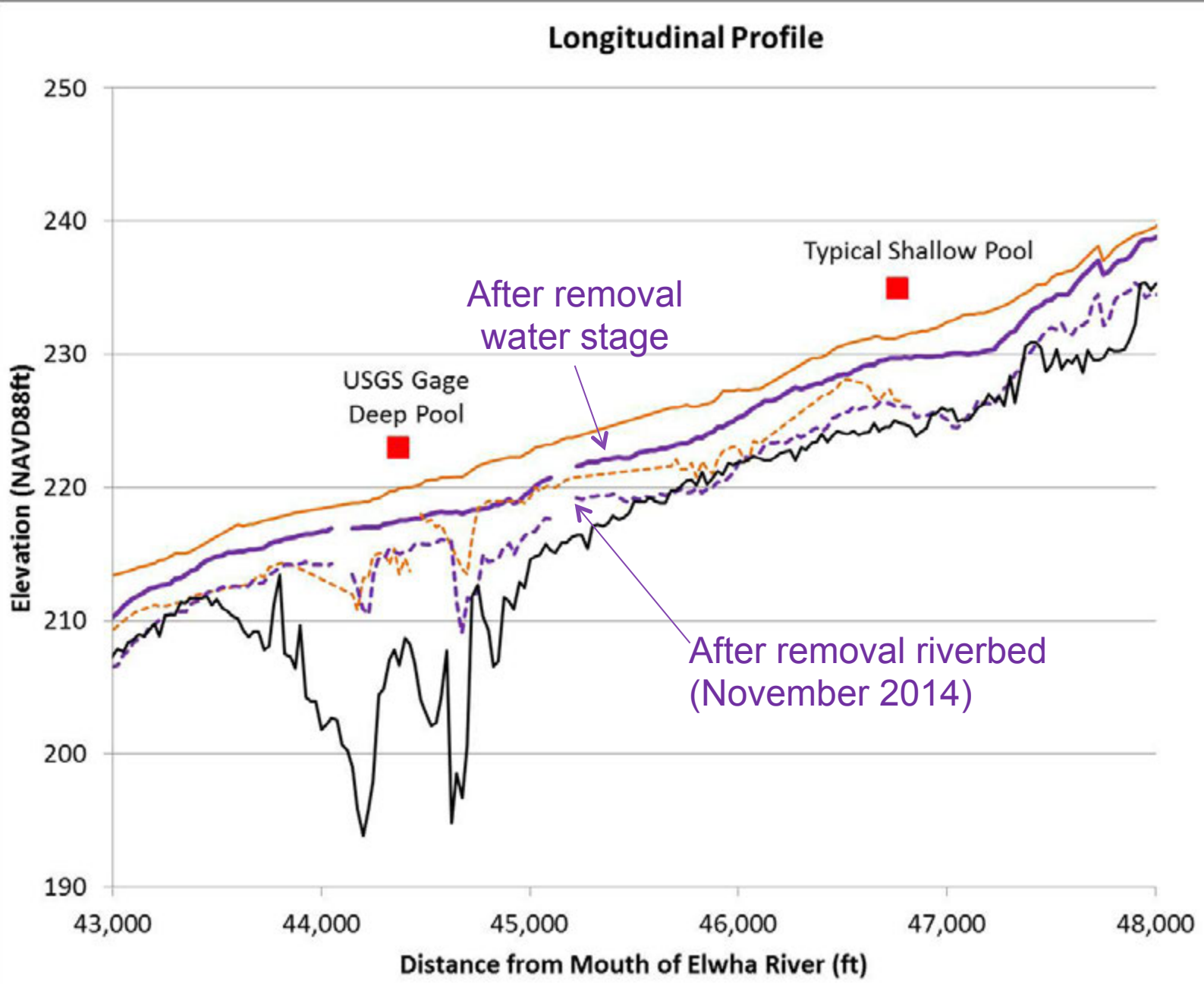
Elevation (NAVD88ft)

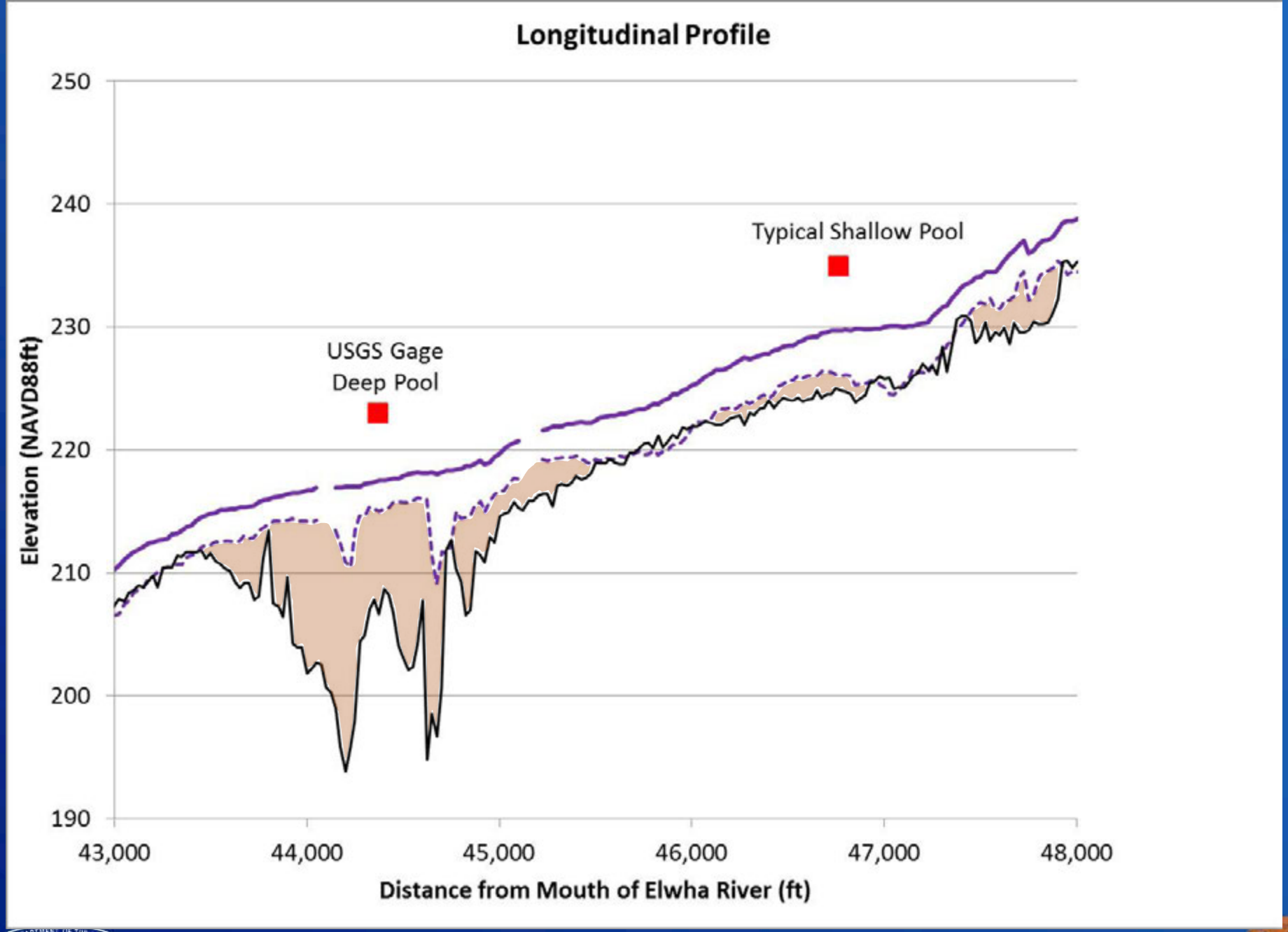
250
240
230
220
210
200
190

43,000
44,000
45,000
46,000
47,000
48,000

Distance from Mouth of Elwha River (ft)


Longitudinal Profile
250
240
230
220
210
200
190
Elevation (NAVD88ft)
43,000
44,000
45,000
46,000
47,000
48,000
Distance from Mouth of Elwha River (ft)
Near Peak Sediment
Impacted Water Stage
Typical Shallow Pool
USGS Gage
Deep Pool
Near Peak Riverbed
Riverbed (Spring 2013)


Longitudinal Profile
250
240
230
220
210
200
190
Elevation (NAVD88ft)
43,000
44,000
45,000
46,000
47,000
48,000
Distance from Mouth of Elwha River (ft)
Typical Shallow Pool
After removal water stage
USGS Gage Deep Pool
After removal riverbed (November 2014)


Longitudinal Profile
250
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230
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190
Elevation (NAVD88ft)
Typical Shallow Pool
USGS Gage
Deep Pool
43,000
44,000
45,000
46,000
47,000
48,000
Distance from Mouth of Elwha River (ft)

Middle River

10 May 2011
Before dam removal

14 Nov 2013
After sediment release

Photos courtesy of Amy East

from Warrick et al. (2015)

Photos courtesy of Mike McHenry

Boston Charley channel 1997

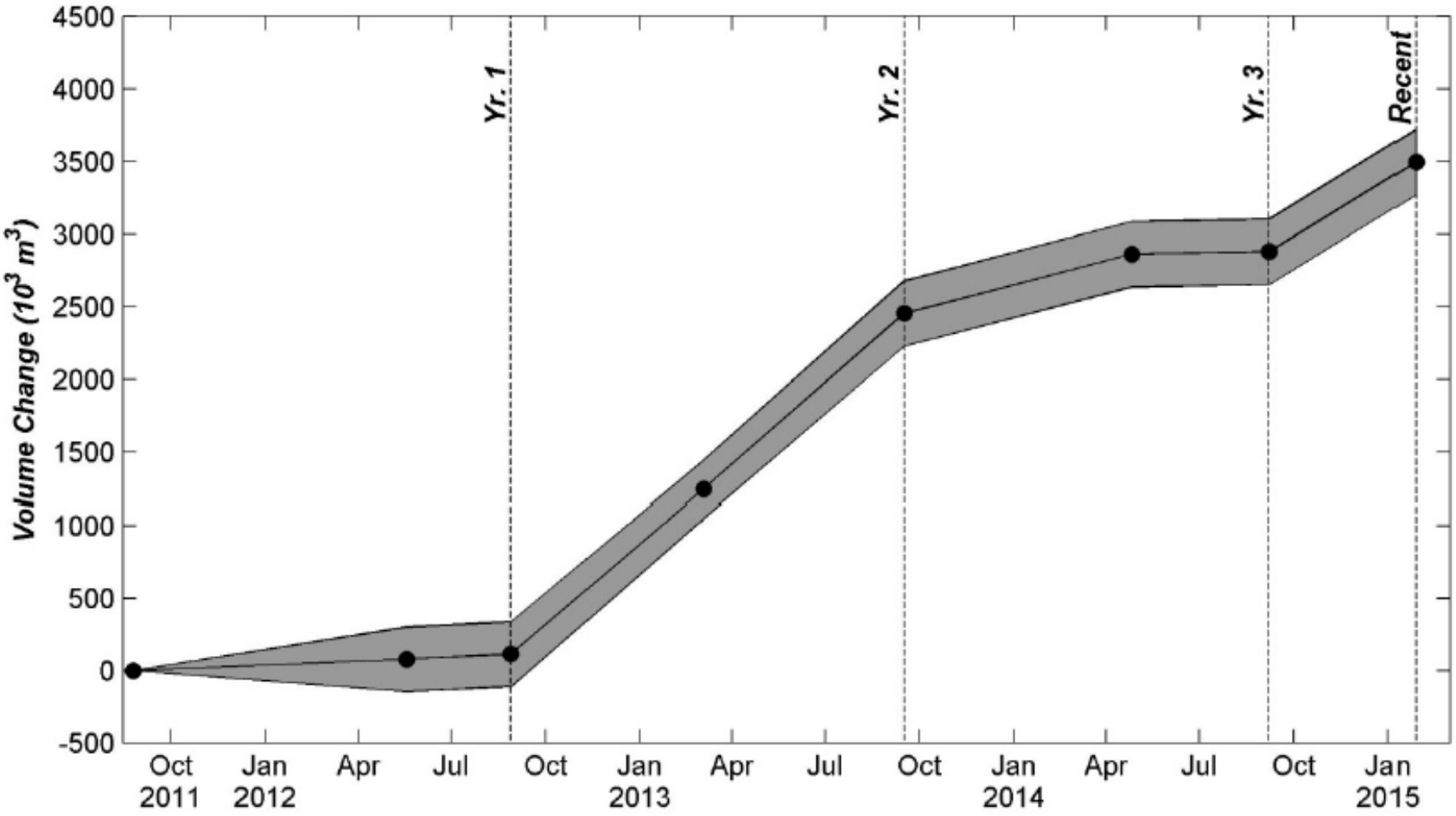
Boston Charley channel 2013


Floodplain channels filled: March 2013, Rkm 5.5


Photo courtesy of Tom Roorda

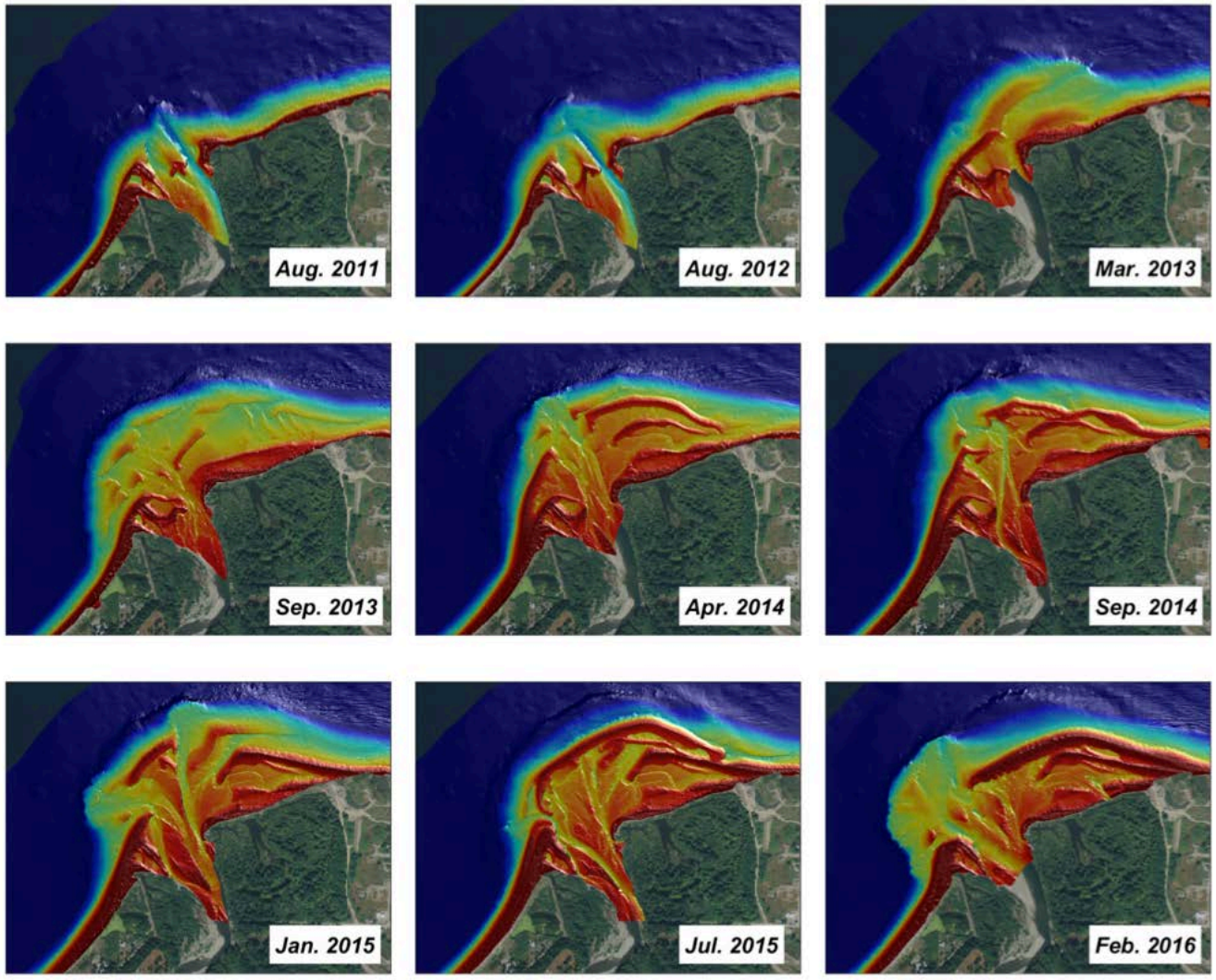
Fall 2012; Photo courtesy Tom Roorda

Cumulative Sediment Reaching Coast



Information courtesy of Jon Warrick, USGS, Santa Cruz, CA

Elwha River mouth, estuary, & nearshore 2011 to 2016



LiDAR slide & work courtesy of Jon Warrick, USGS

Mouth of the Elwha River - April 2014

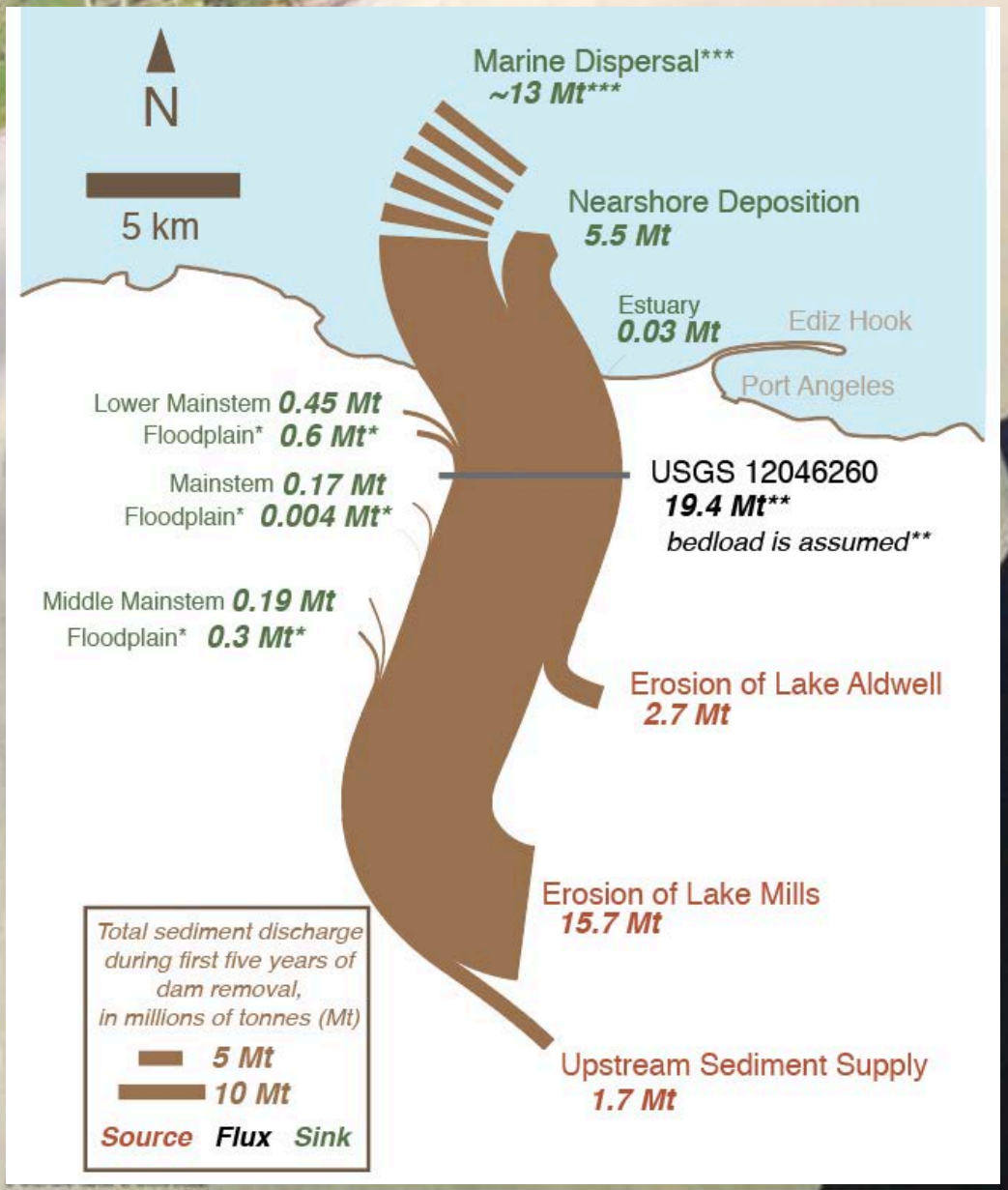
Photo by John McMillan

Mouth of the Elwha River - Nearshore Biota

S. Rubin, N. Elder, et al.

USGS science for a changing world

Elwha River sediment budget



- Over first 2 years, 10.5 million tons of reservoir sediment eroded (~1/3 of stored amount)
- Now, at 4.5 years, 18 million tons eroded, 62% of stored amount
- 90% made it to river mouth
- Rivers can efficiently export sediment even without floods
- By 5th winter, sediment load dominated by upper watershed flux: **dam-removal signal fading!**

Sediment budget, Sept. 2011 to Jan. 2016, modified from Warrick et al., 2015

Photo courtesy of Tom Roorda

Elwha sediment budget details

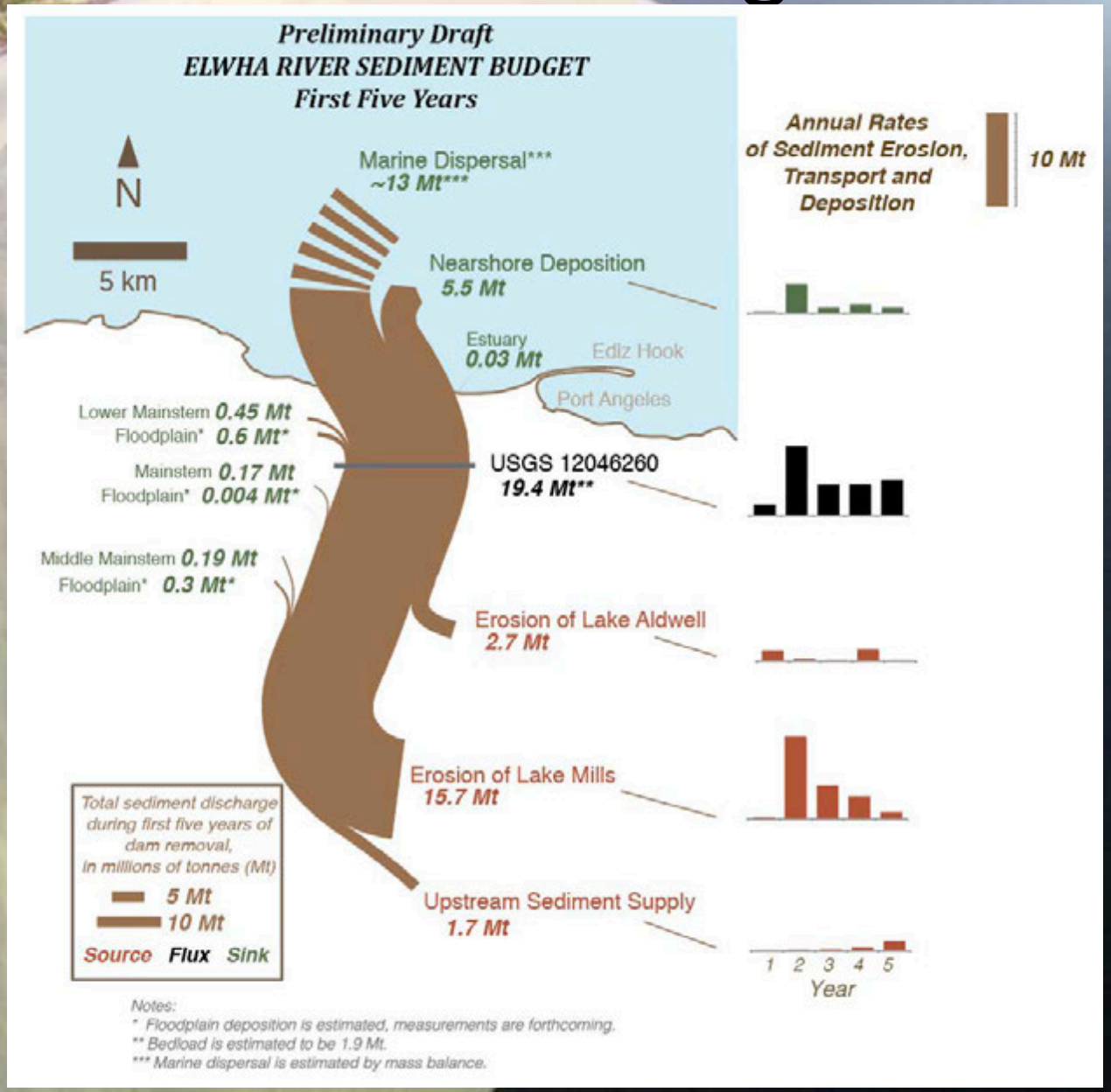
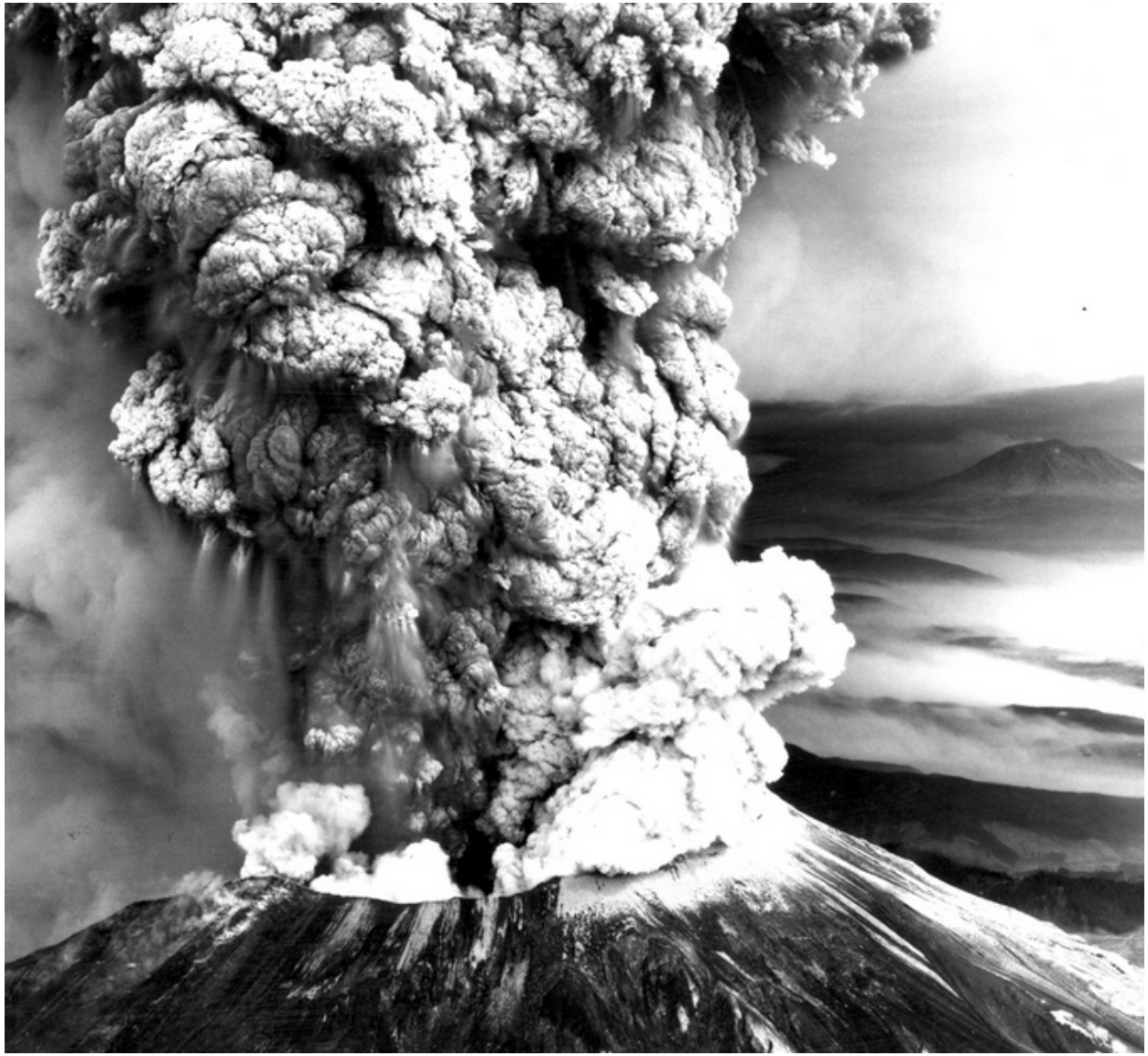
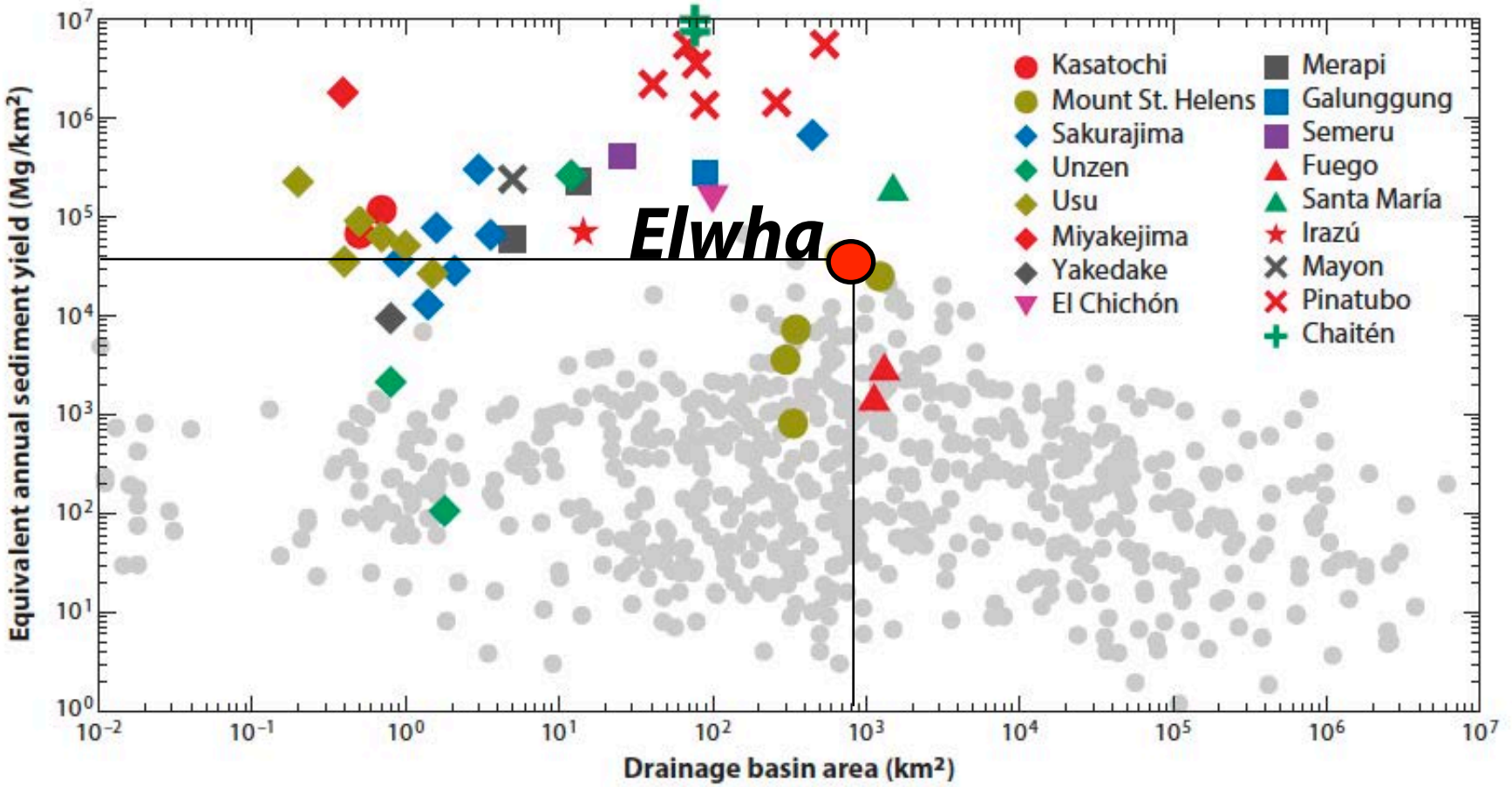


Photo:
Tom Roorda

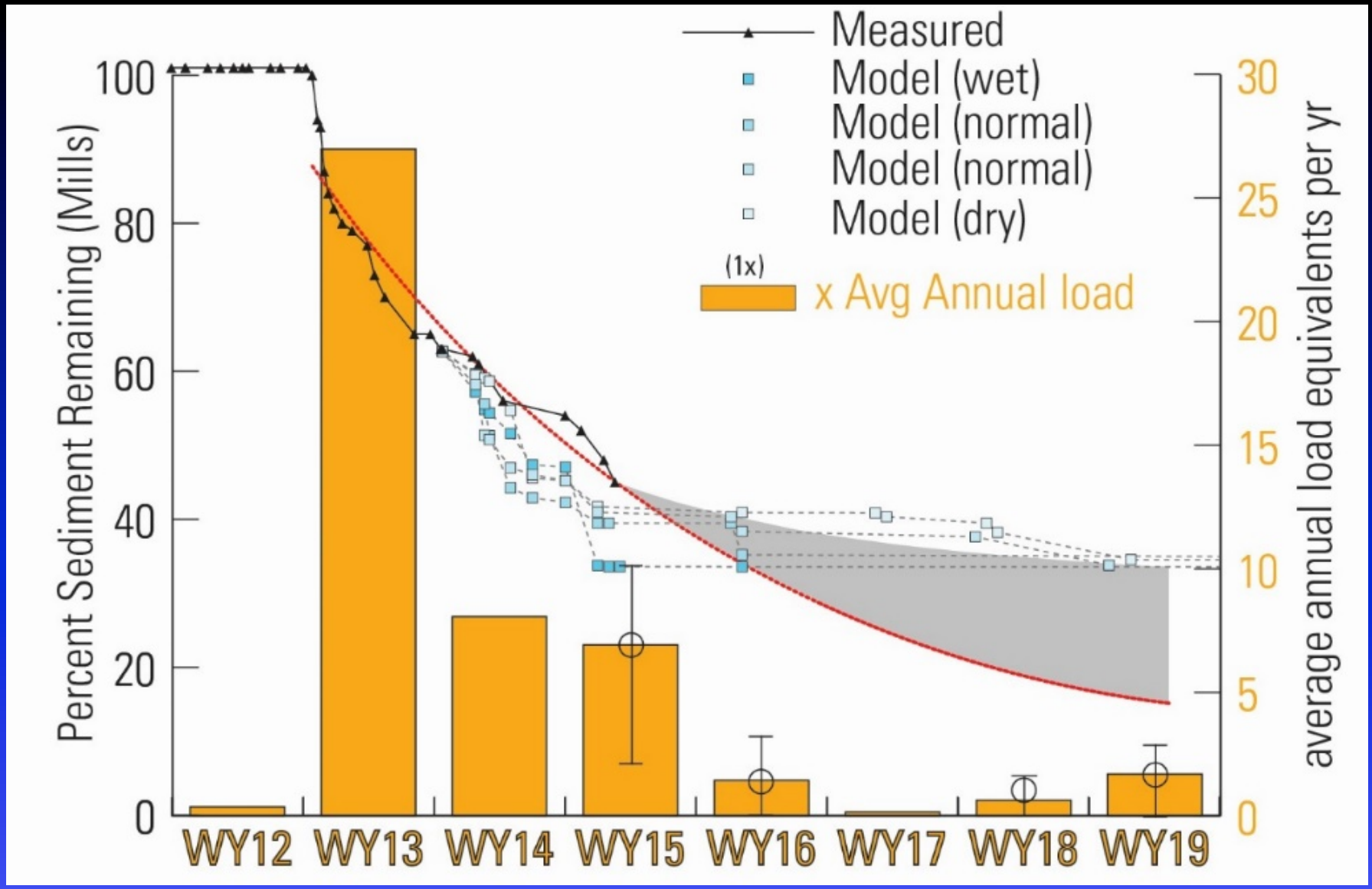
Elwha sediment pulse comparable to May 1980 Mount St. Helens eruption



Size of sediment pulse



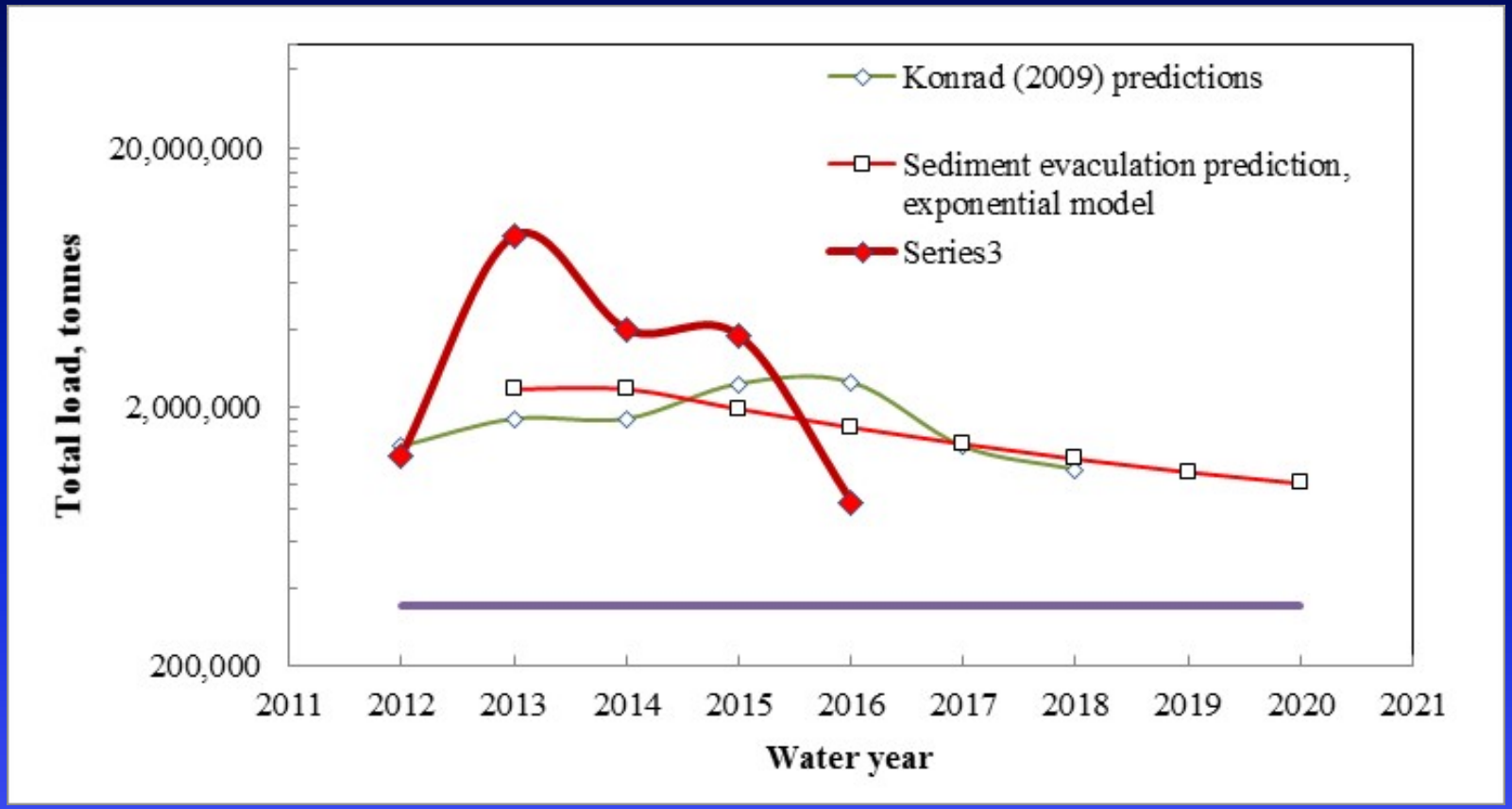
Modified by East from Pierson and Major (2014)



Provisional Analysis by Reclamation
Subject to Change

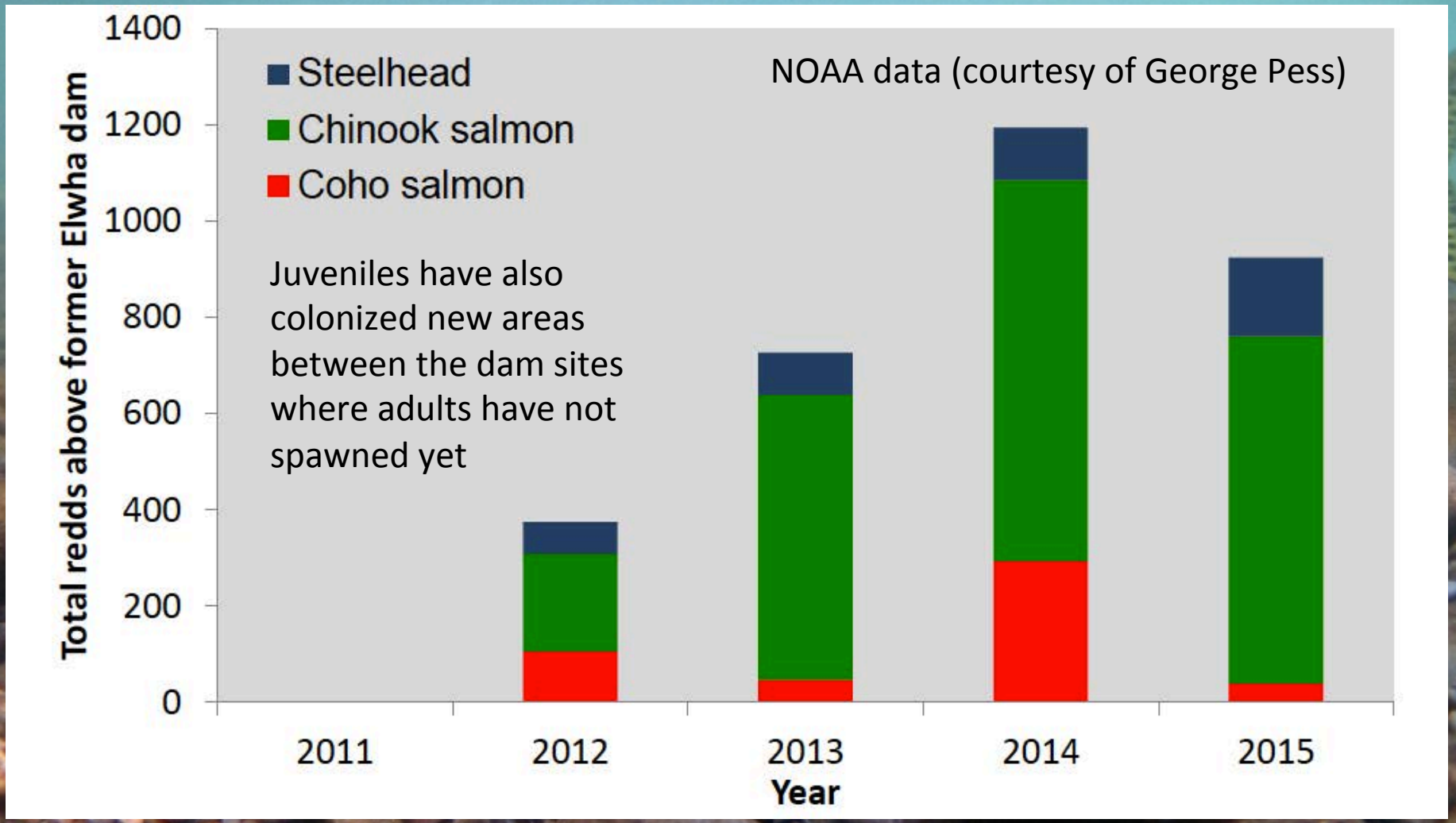
- About 40% mobilized years 0-2
- About 60% mobilized years 0-4

Actual Sediment Evacuation vs. Predictions



USGS Provisional Data; Subject to Change

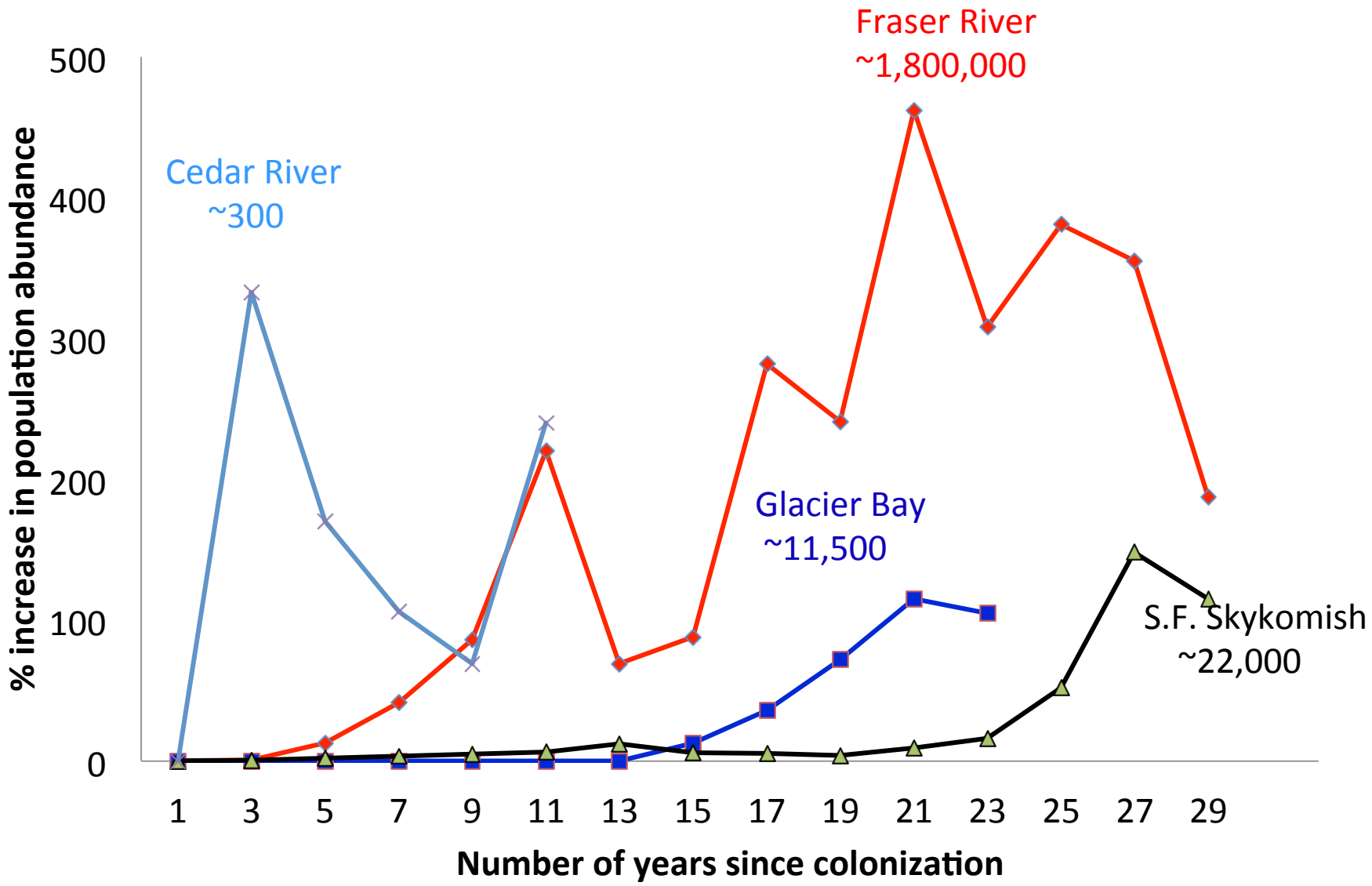
Elwha River fish recolonization



John R. McMillan NOAA/NWFSC

Salmon can successfully colonize newly available habitats

Analysis by George Pess, NOAA



PENINSULA Daily News

Olympic National Park: Fish continue to recolonize Elwha watershed

Biologists say adult chinook salmon, sockeye salmon, steelhead and bull trout have been spotted in the upper stretches of the river.

ROB OLLIKAINEN | Mon Sep 12th, 2016 1:30am | NEWS

PORT ANGELES — Adult chinook salmon, sockeye salmon, steelhead and bull trout were spotted in the upper Elwha River last month, the latest evidence of post-dam removal recolonization, fisheries biologists said.

Recent monitoring has revealed that the fish have passed upstream through the former Elwha and Glines Canyon dam sites, Olympic National Park officials said.

The observation is based on snorkel surveys that spotted fish but did not show the numbers that are swimming above the former dam sites.

"We are thrilled to see this latest confirmation of the success and value of dam removal," acting park Superintendent Rachel Spector said in a Thursday news release.

"As restoration proceeds, the benefits continue to mount along the entire river and throughout its entire ecosystem."

Photo: Amy East, USGS
22 September 2016

Photo: Amy East, USGS
22 September 2016

Key Conclusions after 5 Years:

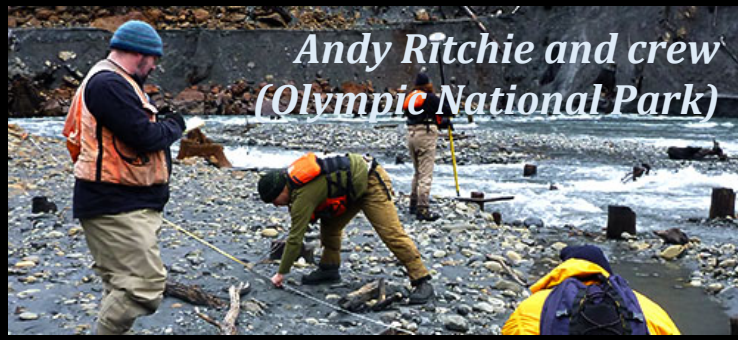
- ~8 million tonnes sediment evacuated in years 1-5
- ~60% of total trapped volume
- Most (90%+) of the sediment delivered to Puget Sound (22 km)
- Represents major sediment disturbance experiment
- More sediment and faster than expected
- Salmon are returning, trees are growing, ecosystem responding
- The Elwha is trending back toward a natural functioning river.

2015; Photo courtesy John Gussman © John Gussman

Thank you


Tim Randle, Jennifer Bountry (USBR)


Jeff Duda (USGS)


Andy Ritchie and crew (Olympic National Park)


Ian Miller (WA Sea Grant)

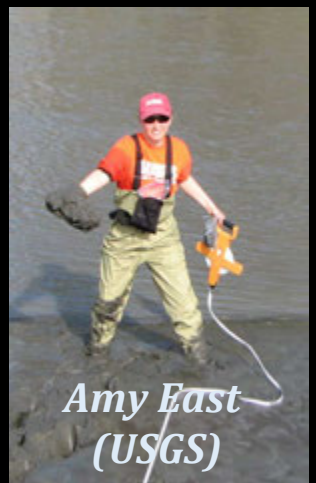

Melissa Foley (USGS)


Andrea Ogston and Emily Eidam (UW)


George Pess and crew (NOAA)

Guy Gelfenbaum and crew (USGS)


Matt Beirne and the Lower Elwha Klallam Tribe


Amy East (USGS)


Chris Curran and crew (USGS)