Linking sediment and channel dynamics to hydrologic regimes below dams

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Big Cliff Dam, N. Santiam River, Oregon USA
Drivers

Direct change in Q
• dams, diversions

Indirect change in Q
• climatic trends/shifts
• landuse (urbanization, forest landuse)

Change in sediment supply
• dams
• gravel mining
• landuse, (urbanization, forest harvest)

Consequences
Altered Flow (Q) and Sediment (Qs) Regimes

Drivers

Consequences

Physical

Ecologic

Social & Economic
Dams have the most direct impact on flow and sediment regimes

- Dams may or may not affect the flow regime
- Virtually all dams affect the sediment transport regime by trapping sediment
Using Lane’s Balance to predict downstream changes

Lane’s Balance

(Sediment LOAD) \times (\text{Sediment SIZE}) \propto (\text{Stream SLOPE}) \times (\text{Stream DISCHARGE})

FIGURE 2.1. Schematic of the Lane relationship qualitative analysis. (After Lane, 1955)
Scenario 1. Reduced Sediment
A. Mediterranean rivers post 1900: dams, afforestation, gravel mining

less sediment

Qs ↓

Q ~

Diagram showing a balance scale with "SEDIMENT SIZE" and "STREAM SLOPE" on either side, resulting in less sediment and a change in Qs.
Scenario 1. Reduced Sediment

A. Mediterranean rivers post 1900: dams, afforestation, gravel mining
Channel incision and bed degradation
Arno River at Empoli, Italy
Scenario 1. Reduced Sediment

A. Mediterranean rivers post 1900: dams, afforestation, gravel mining
Scenario 1. Reduced Sediment

B. Clackamas River, Oregon: multiple dams

less sediment

$Q_s \downarrow$

$Q \sim$
Scenario 1. Reduced Sediment
B. Clackamas River, Oregon: multiple dams
Textural coarsening below River Mill Dam
Clackamas River, Oregon
Scenario 1. Reduced Sediment

B. Clackamas River, Oregon: multiple dams

Coarsening, armoring

less sediment

Qs ↓

Q ~
Scenario 1. Reduced Sediment
C. Deschutes River, Oregon: hydroelectric and reregulation dams
Biogenic Dunes
Deschutes River, Oregon
Scenario 1. Reduced Sediment
C. Deschutes River, Oregon: hydroelectric and reregulation dams
Scenario 2. Reduced Sediment and Reduced Flow
A. Colorado River, Arizona, below Glen Canyon Dam

less sediment

less water

Qs ↓

Q ↓
Large decrease in eddy sand bars
Grand Canyon, Colorado River
Scoured pools and riffles (Grams and Schmidt, 2002)
Encroachment of vegetation
Lodore Canyon, Green River
Grams and Schmidt, 2002
Scenario 2. Reduced Sediment and Reduced Flow
A. Colorado River, Arizona, below Glen Canyon Dam
Tributaries deliver sediment downstream, mitigating dam effects
Grand Canyon, Colorado River
Scenario 2. Reduced Sediment and Reduced Flow

B. Trinity River, California: large upstream dam

- Less sediment
- Less water
- Reduced flow (Qs)
- Reduced discharge (Q)
Riparian encroachment
Trinity River, California
Scenario 2. Reduced Sediment and Reduced Flow
B. Trinity River, California: large upstream dam

Coarsening

incision, narrowing

Qs ↓

Q ↓
Impacts of modified channel morphology on salmonid habitat
Trinity River, California
images courtesy S. McBain
Framework for predicting downstream channel response

South Fork Yuba River, California

Waiapu River, New Zealand
Tools and Approaches
\[ S^* = \frac{(Q_s^*)^{0.5} (D^*)^{0.75}}{Q^*} \]
Where do we stand with respect to quantitatively predicting the downstream geomorphic response of rivers to dams?

<table>
<thead>
<tr>
<th>Response</th>
<th>Vertical Adjustments</th>
<th>Textural Adjustments</th>
<th>Lateral Adjustments (with tribs)</th>
<th>Lateral Adjustments (no tribs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Magnitude</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Timing</td>
<td>+</td>
<td>?</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Longitudinal Extent</td>
<td>+</td>
<td>?</td>
<td>+</td>
<td>?</td>
</tr>
<tr>
<td>Persistence</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Bringing it all together

Geology
- Rock properties (erodibility)
- Deformation and structure
- Processes

Climate
- Precipitation type, intensity and duration

Topography
- Relief
- Drainage Density

Sediment Supply

Sediment Transport Regime

Hydrologic Regime

Channel and valley floor morphology

Dams

Geologically-controlled landforms and events
("history")

Aquatic Habitat/Biology

Basin Scale

Channel and reach scale
Bringing it all together: IDRAIM

Stream hydromorphological evaluation, analysis and monitoring system

(Rinaldi et al, 2011)

Phase 1: Characterization of the fluvial system

Phase 2: Past evolution and present river conditions

Present state

Phase 3: Future trends

Phase 4: Management

Italy: densely populated country and high risk level for fluvial systems
Managing hydrologic and sediment regimes together to meet ge-ecological objectives in dynamic landscapes

- Modify flow
- Modify sediment transport regimes
- Modify sediment supply
- Engineer channels and habitat
How to reintroduce sediment into a river...

Sediment Starved Reaches

Remove dam

Blow & go

Stepped removal

Add sediment

Dump truck

Gardening

Sediment Rich Reaches

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Dam removals in the United States

From O’Connor et al., 2015
Recent Pacific Northwest Dam Removals

Elwha Dam
Elwha River, WA

Glines Canyon Dam
Elwha River, WA

Condit Dam
White Salmon River, WA

Marmot Dam
Sandy River, OR

Brownsville Dam
Calapooia River, OR

Savage Rapids Dam
Rogue River, OR
Learning from dam removals: 
*Upstream reservoir erosion*

- 15 dam removals
- data for first 1-2 yrs

(Sawaske & Freyberg, 2012)
STAGED REMOVAL

> 55% SAND

Mass movement in saturated sediments

GRAVEL

COHESIVE SEDIMENT

STAGED REMOVAL

Grant & Lewis, in press

Days Since Dam Removal

Volume of Reservoir Sediment Eroded
Learning from dam removal: Downstream sediment transport

<table>
<thead>
<tr>
<th>Dam</th>
<th>Distance Sediment Transported (km)</th>
<th>Distance Downstream from Dam to River Mouth (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condit</td>
<td>5 km</td>
<td>21 km</td>
</tr>
<tr>
<td>Glines</td>
<td>12 km</td>
<td>21 km</td>
</tr>
<tr>
<td>Elwha</td>
<td>13 km</td>
<td>172 km</td>
</tr>
<tr>
<td>Marmot</td>
<td>6 km</td>
<td>48 km</td>
</tr>
<tr>
<td>Savage Rapids</td>
<td>2 km</td>
<td>172 km</td>
</tr>
<tr>
<td>Brownsville</td>
<td>0.6 km</td>
<td>62 km</td>
</tr>
</tbody>
</table>

*Bar thickness suggests fraction of total load

Grant & Lewis, 2015
Strategies for delivering sediment to rivers

Dump Truck

N. Umpqua River
Photo: R. Deibel

Gardening

Mokelumne River
Photo: G. Pasternack
Managing sediment transport in large rivers

- Monitor sediment flux from tributaries
- When sediment volumes exceed threshold values, perform High Flow Experiment
- Monitor results in terms of channel and ecological objectives

*Colorado River: Wright & Kennedy, 2011*
Overarching goal of eflows: Maintain alluvial river integrity

1. Spatially complex channel morphology
2. Flows and water quality are predictably variable
3. Frequently mobilized channel morphology
4. Periodic channelbed scour and fill
5. Balanced fine and coarse sediment budget
6. Periodic channel migration and/or avulsion
7. Functional floodplain
8. Infrequent channel resetting floods
9. Self-sustaining riparian plant communities
10. Naturally fluctuating groundwater table

Trush et al, 2000
Linking the hydrograph to both geomorphic processes...

Image courtesy S. McBain
AND ecological processes (simultaneously!)
With a drainage basin perspective

Flitcroft et al., in review
Ultimately, our challenge is to help describe the “tradeoff space” for river managers.