Reservoir Sedimentation: A Focus on Upstream Sediment Sources

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Reservoir Facts

- 42,000 large (over 15 m tall) dams worldwide
- Number increases substantially for smaller size reservoirs:
  - 2,000,000 in US with <50 acre-ft capacity from National Inventory of Dams
- USDA Small Watershed Program - Helps communities and rural areas reduce flooding
  - Since 1948, over 11,000 flood control dams have been built nationwide (47 states)
  - In Oklahoma 2,105 dams have been built in 121 watersheds
  - Flood protection for more than 2 million acres and close to $2 billion infrastructure
  - Estimated $53 million needed to rehabilitate these structures in Oklahoma alone
- Prediction: Population and economic growth means greater reliance on reservoirs
General Issues

- Streams in dynamic equilibrium: Sediment In = Sediment Out
- Dam construction creates impounding river reach:
  - Low flow velocities = Efficient sediment trapping!
- Accumulate sediment and lose storage capacity until equilibrium is again achieved:
  - Loss in storage capacity = No flood retention/protection = Loss in hydropower, navigation, recreation, and environmental benefits
- Sustainable long-term use means managing sediments as well as water:
  - “…structures are designed and operated to continuously trap sediment, without specific provisions for sustained long-term use” (Morris and Fan, 2010, Reservoir Sedimentation Handbook)
In-Reservoir Issues

- Obstruct intakes and greatly accelerate abrasion of hydraulic machinery
- Density currents can transport sediments significant distances in reservoir and block low-water intakes
- Localized deposits in delta region can create flooding, impact navigation, and alter ecology
Downstream Issues

- Reservoirs can drastically alter flow conditions and habitat (temperature)
- When you cut off sediment supply, water becomes “hungry” for sediment
  - Streambed degradation, streambank failure, and increased scour at structures
  - Streambed can become armored reducing spawning habitat

http://www.americanwhitewater.org
Design Strategy for Reservoirs

**Historically:** Build it large and control erosion upstream, but upstream erosion control unsuccessful.

**Future Design:** Replace concept of limited reservoir life with concept of managing both water and sediment.

“...preservation and continued utilization of existing reservoir sites, not the continued exploitation of a shrinking inventory of potential new sites” (Morris and Fan, 2010, Reservoir Sedimentation Handbook)
Sediment Management

- Control Sediment Deposition: Route sediments beyond the storage pool and sediment placement/deposition

- Remove Deposited Sediment: Sediment removal by hydraulic flushing or dredging

- Reduce Sediment Inflow: Reduce sediment inflow by erosion control and upstream sediment trapping
  - Upland erosion (rill and interill erosion)
  - New sources being considered: gullies and streambanks

http://water.usgs.gov/edu/gallery/sediment-influx2.html
Upstream Sediment Source: Streambanks

- Channel erosion is known to be a significant contributor to total sediment and nutrient loading
- “...sediment in streams originated more from channel and bank erosion than from soil erosion” (Tomer and Locke, J. Soil and Water Conservation CEAP Watershed Studies)
- Sediment from streambanks can account for up to 85% of watershed sediment yields
Upstream Sediment Source: Streambanks

Mass Wasting

Subaerial Processes

Fluvial Erosion

(Langendoen, 2000)
April 3rd, 2009

May 2nd, 2009

Sept. 23rd, 2009
7.8 to 20.9 m of bank retreat during the summer of 2009 over a 100 m reach.
Eroded Banks in Watershed
Site A - Unprotected
Watershed Area: 363 km²
Reach Length: 190 m
Average of 33.7 m of lateral migration
Loading Rates

- ~10-15% of dissolved P load from streambanks
- TP from streambanks on order of that measured in stream
- 3x to 5x reduction in contributed WSP and TP per m of bank per year with riparian protection

Other Studies:
7 to 10% of annual total phosphorus (TP) in Minnesota (Sekely et al., 2002), 14 to 24% of TP in Denmark (Laubel et al., 2003), 21 to 62% of annual loads for a Danish stream with cohesive banks (Kronvang et al., 2012)
Estimating Retreat Rates

- Retreat rates help to estimate loadings, design stabilization, and improve watershed management
- Potential strategies:
  - Aerial imagery
  - Erosion pins
  - Qualitative indices
  - Process-based modeling
Estimating Retreat Rates

- Streambank retreat
  - Subaerial processes (PWP, weathering)
  - Fluvial erosion (direct removal by flow)
  - Bank failure (slope instability)
- Retreat rates
  - Hydrology/climate
  - Soil type
  - Riparian protection
  - Adjacent land use

Estimating retreat is difficult!
- Magnitude and episodic nature of erosion
- High degree of variability in factors controlling erosion
Quantifying Erodibility

- Excess shear stress equation (1965):
  \[ \varepsilon_r = k_d (\tau - \tau_c)^a \]
  
  - \( \varepsilon_r \): erosion rate (cm s\(^{-1}\))
  - \( k_d \): erodibility coefficient (cm\(^3\) N\(^{-1}\) s\(^{-1}\))
  - \( \tau \): average hydraulic boundary shear stress (Pa)
  - \( \tau_c \): critical shear stress (Pa)
  - \( a \): empirical exponent (assumed = 1)

- Benefit to moving to nonlinear, mechanistic detachment models

- Empirical relationships estimated from soil parameters – Large degree of uncertainty

- Must be measured in situ – Jet Erosion Tests (JETs)
Jet Erosion Tests (JETs)

- Commonly used to measure $\tau_c$ and $k_d$ in situ
- Based on the rate of scour and velocity of jet

(Al-Madhhachi et al, 2013, 2014a, 2014b)
Conclusions

- Reservoirs are critical features for long-term sustainability of water supplies
- Shift from building new large capacity reservoirs with assumed life-span (focus on water) to focusing on extending life-time of existing reservoirs (water and sediment management)
- Upstream erosion control critical for extending life-span of reservoirs, but we must consider all sediment sources