The effects of flooding and dam management on large alluvial rivers: evidence for an inter-dam sequence and an alternative state

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Upper Missouri River

- Garrison Dam, 1953
- Oahe Dam, 1959
- 15 dams on the main stem
- Largest reservoir storage in U.S.

- Garrison Dam Segment used for:
  - Recreation
  - Irrigation
  - Water supply
  - Flood control
  - Fisheries
  - Habitat for endangered species
  - Electricity generation

- Unintended effects
  - Navigation
  - Ice Jams
  - Endangered species
    - Least tern
    - Piping plover
    - Pallid sturgeon
Motivation

- Largest flood since Garrison Dam regulation
- 24 million acre-feet of runoff generated (10 million typical)
- Estimated as a 500-year event
- Began in May 2011, releases peaked in June at ~150,000 cfs
- Flow did not recede to normal annual peaks at Bismarck until late September
Another dam study...

Degradation of the Missouri River near Bismark, ND, is predicted, but aggradation has occurred because of backwater effects of Oahe Reservoir, located immediately downstream...

Grant et al., 2003. A Peculiar River.

Figure 2. Expected textural, bedform, and planform adjustments of alluvial rivers in response to changing sediment supply in relation to transport capacity.
Major components of the study

- **Long-term effects of dam management on channel morphology**
  - Dam interactions are important for channel adjustment

- **Effects of the 2011 flooding**
  - Channel morphology
    - Islands, banks, delta
  - Sediment transport mechanics
    - Sediment balance from flood
    - Aeolian transport after the flood
  - Vegetation
    - Regrowth
    - Large Woody Debris

- **Predictions of change after the flood**
Geomorphologic units in the Garrison Dam Segment

Garrison Dam downstream
- **Dam Proximal** is eroding the bed, banks, and islands.
- **Dam Attenuating** is eroding the bed and banks. Islands are metastable.

Dam interaction units
- **River-Dominated** has increase in islands and bars, minimal change in A.
- **Reservoir-Dominated** has aggrading islands, bars, flooded meander bends.

Oahe Dam upstream
- **Reservoir** reach is remarkably stable, no change in A.

*Skalak et al., 2013. Large dams and alluvial rivers in the Anthropocene.*
What are long-term effects of the dams?

Historical cross-sections (USACE, 1946-2007)

\[
\frac{BE_{t1} - BE_{t2}}{t1 - t2}
\]

BE - minimum bed elevation
T - time in years

\[H - E_i = \Delta E_i\]

H - bankfull during dam operations
E - survey elevation at location i

\[
\sum \left( \frac{(\Delta E_i + \Delta E_i + 1)}{2} \right) \times (D_i - +D_i + 1) = A
\]

D - cross-stream distance
A - cross-sectional area

Space for time substitution for natural variability in channel geometry
All sites eroding

12 of 14 eroding

4 eroding, 5 depositional

9 of 11 depositional

All depositional

4 eroding, 5 depositional
Spatial patterns in channel capacity

Channel Capacity Change

Percent change in cross-sectional area

Erosional

Predicted attenuating effects

Depositional

Oahe Dam effects

River km downstream of Garrison Dam
Temporal trends in channel capacity

The diagram shows the percent cross-sectional area change from 1950s to 2010 for different transect types: Dam Proximal Zone, Attenuating Zone Transects, River Dominated Transitional Transects, Reservoir Dominated Transitional Transects, and Reservoir Zone Transects. The 25%-75% range is indicated by colored bands for each transect type.
Bed stabilization

Continued adjustment
Trends in lateral mobility

Lateral stabilization
What happened to channel islands/habitat?

- Aerial photos for segment between Garrison Dam and Bismarck (1950 to 1999)
- Bank Delineations, Island Change
- 0.7% difference in discharge between these years
- 1999 orthorectified, used to georectify 1950
  - 10 control points

43% loss in islands
16% gain in islands
150% gain in islands
What controls longitudinal patterns in sedimentation?
**Idealized Inter-Dam Morphology:**

**River Zones:**
- Dam Proximal
- Attenuating
- River-Dominated Transitional
- Reservoir-Dominated Transitional
- Reservoir

**Morphological Features:**
- Removal of islands in channel
- New vegetation growth and stabilization of point bars
- Sandbar islands remain but island movement is steady and not episodic due to managed flow rates.
- Creation of large islands on the outside of bends from sediment drop off and backwater effects.
- Inundated scroll bars large tree die off (cyclical due to changing reservoir level) and deposition of trees from storms.
- Submerged delta front created during low reservoir level.
- Reservoir has minor deposition.

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Skalak et al., 2013. Large dams and alluvial rivers in the Anthropocene.
Possible dam interactions within U.S.

- Up to 25 km: significant geomorphic effects (Williams and Wolman, 1984)
- Up to 100 km: discernible geomorphic effects (Schmidt and Wilcock, 2008; Hupp et al., 2009)
- Up to 1000 km: minor effects (Williams and Wolman, 1984; Jacobson et al., 2009)

**USACE National Inventory of dams**

**Distances between dams on major rivers of U.S.**

Inter Dam Distances on the Major Rivers of the US

Legend:
- >100km to next downstream dam
- 25-100km to next downstream dam
- <25km to next downstream dam
- No downstream dam
2011 flood effects on channel morphology

Continued loss of significant landforms

42% loss in islands
13% gain in islands
25% gain in islands
Island Area Change 2010-2012

Cumulative Island Area Change

% Island Difference Per 10 River Miles

Distance (mi)

Island Area Change (m)
Aquatic Terrestrial Transition Zone

The graph shows the relationship between shoal slope and distance from the dam in different zones:

- **Dam Proximal**: Data points indicate a decrease in shoal slope as distance from the dam increases.
- **Dam Attenuating**: A transition zone with both increasing and decreasing trends in shoal slope.
- **River Dominated Transitional**: A zone characterized by a significant change in shoal slope.
- **Reservoir Dominated Transitional**: A transitional zone with a gradual change in shoal slope.
- **Reservoir**: Data points showing a consistent shoal slope.

The p-value for the trend is 0.00686, indicating a statistically significant relationship between shoal slope and distance from the dam.
• Repeat LiDAR data sets were flown over ~30 river miles of the river in 2009 & 2012

• We examined deposition in the ~77.7km$^2$ flooded area around Bismarck

• We found that there was ~13,700,000 m$^3$ deposition in this section
Vertical accumulation from flooding

Estimated Volume of sand

River Mile

m$^3$

- 500,000
- 1,000,000
- 1,500,000
- 2,000,000
- 2,500,000
- 3,000,000
- 3,500,000
- 4,000,000

10 20 30 40 50 60 70 80 90 100
Shift to an aeolian transport regime

- Flood deposits are composed of very fine sand to medium sand at all Sites
- Silt and clay (<64 microns) represents <4% of the material
- Transport is primarily saltation
How can we measure wind transport?

- Sand traps set at 3 sandbar locations in 2012 & 2013
- At each location, 3 trap sets installed
  - 1) no vegetation area
  - 2) minimal vegetation area
  - 3) Willow regrowth area
- Traps checked every 2-4 weeks
  - samples analyzed for total mass and grain-size distribution
Vegetation Cover Types

Bare Sand

Sparse Vegetation

Dense vegetation
Utilizing Remote Sensing Data

- Using remote sensing derived vegetation data we examined vegetation recovery over 110 river miles downstream of the Garrison Dam
- Bare sand increased 780% Between 2010-2012 (2.2 km$^2$ to 17.2km$^2$)
- In 2013 the amount of bare sand decreased 42% to 10.0km$^2$

Will This Rate Continue?
Deposition Controls Vegetation Regrowth

- Thin deposition allows vegetation to recover quickly due to regrowth from pre-flood surfaces.
- Regrowth occurs in patches across areas of bare sand.
Thick Deposition

- Thick sand limits vegetation recovery
- The high aeolian activity suppresses vegetation regrowth
- Vegetation repopulates from the edges at a much slower rate
How Long Will the Sand Blow?

What We Found

• High sediment flux on Bare Sand surfaces limit vegetation regrowth

• We observe little to no armoring of the surface

• The unvegetated surface is deflating

• Vegetation quickly covers newly created Bare Sand in areas of thin deposition

• Areas of thick deposits have slow vegetation recovery rates

We Predict:

• Vegetation recovery will slow as most areas of thin vegetation have stabilized leaving only thicker deposits which are much slower to revegetate.

• We estimate that the aeolian activity will remain elevated in this reach for 15 to 20 yrs
How did wood transport and storage change?

- Large wood is critical for stream habitat, navigation concerns, and sediment storage.
- We determined how the flood changed the distribution and pattern of wood storage.
Wood distribution

Discrete log jam

Diffuse log jam
Flooding effects on vegetation

Pre and post flood forested area

Pre and post flood wood distribution
Prediction of change
iRIC modeling
Falling limb
80,500 ft³/s

Rising limb
87,500 ft³/s

Peak
149,000 ft³/s

Bismarck gaging station

High: 12 mm
Low: 0 mm

High: 6 mm
Low: 0 mm
Evidence of An Alternative State

Change in landscape structure
• Loss of islands
• Gain of bank attached islands and delta
• Change in planform

Change in ecological function
• Lotic to lentic processes
• Loss of tern and plover habitat
• Pallid sturgeon larvae stagnation
• Loss of riparian vegetation communities
Conclusions

• Long-term management on the Missouri River created a new landscape state.
• The 500-year event did not perturb this state into a new configuration.
• The geomorphically effective (frequency and magnitude) event is the management condition, not the flood of record.
• Other factors to consider moving forward
  – Changing climate
  – Changing land use
How does changing flood frequency impact channel morphology?

• At six pilot locations, we can demonstrate that flood frequency is changing as a result of changing precipitation.
  – What does this change in flood frequency do to changes in the channel morphology?
    • Stage discharge analysis
    • Cross-sectional analysis at gage location
    • Aerial photo analysis
Cooperators

Morton County WRB
Lower Hart WRB