Examining Higher Hydraulic Gradients in Restored Streams and the Implications on Hyporheic Exchange

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Overview of Presentation

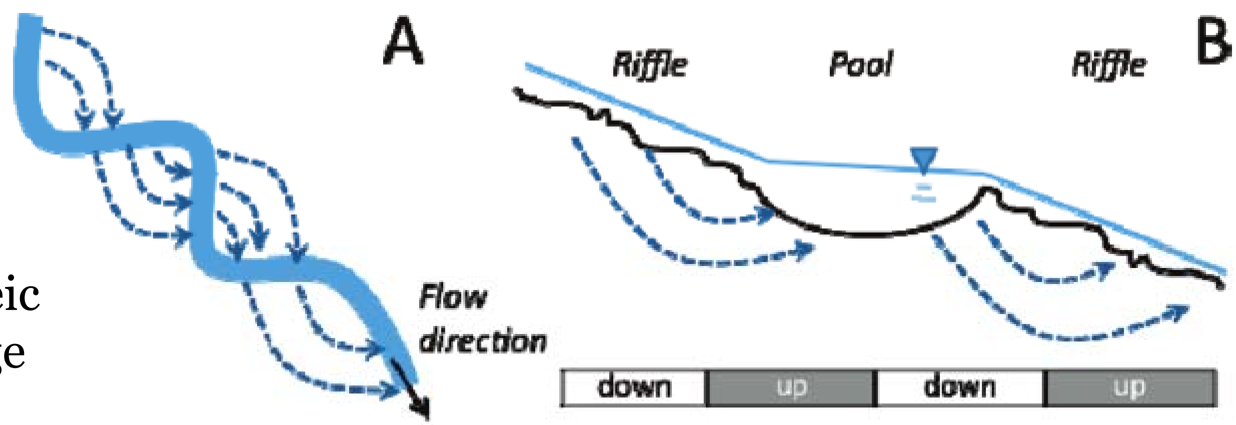
- Hyporheic exchange
- Studies on stream restoration, especially about hydraulic gradients and river stage
- Our research
- Future research and implications on hyporheic exchange

Hyporheic Exchange Overview

- Boulton et. al., 1998 :
  - Hyporheic Zone: an "active ecotone between the surface stream water and groundwater"
  - Hyporheic Exchange: the "exchanges of water, nutrients, and organic matter occur [in the hyporheic zone] in response to variations in discharge and bed topography and porosity"

    discharge → hydraulic head

Lateral hyporheic exchange



Vertical hyporheic exchange

Figure from Hester and Gooseff, 2010

Hyporheic Exchange Overview

Functions commonly associated with:

Vertical hyporheic exchange

- Lotic habitat
  - Invertebrates & macroinvertebrates
  - Fish
- Nutrient cycling
  - Consumption & transformation by microbes
  - Oxygen and energy cycling
- Pollutant buffering
  - Sink for hard metals and hydrocarbons
- Temperature regulation
  - Surface water vs. groundwater
  - Habitat quality, especially during low flow
  - Constraint on biogeochemical reactions

Lateral hyporheic exchange

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  - Consumption & transformation by microbes
  - Oxygen and energy cycling
- Pollutant buffering
  - Sink for hard metals and hydrocarbons

Stream Restoration Research

- Vertical hyporheic exchange:
  - Hydraulics:
    - Crispell and Endreny, 2009: Batavia Kill, NY
    - Hester and Doyle, 2008: simulation models, flume tests, field experiments in Craig Creek (small mountain stream) near Blacksburg, VA
  - Biogeochemistry:
    - Lautz and Fanelli, 2008: 3rd order Red Canyon Creek in Lander, WY (semi-arid watershed)
- Lateral hyporheic exchange:
  - Hydraulics and Biogeochemistry:
    - Kasahara and Hill, 2007: 2 lowland stream reaches of Boyne River, Ontario, CA (intensive agri. watershed)

Science Question

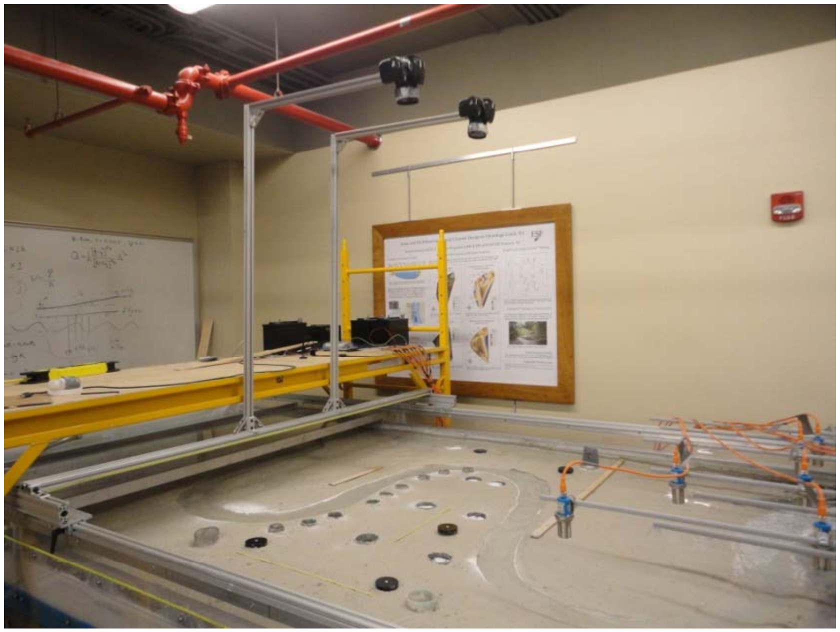
How do in-channel stream restoration structures affect:

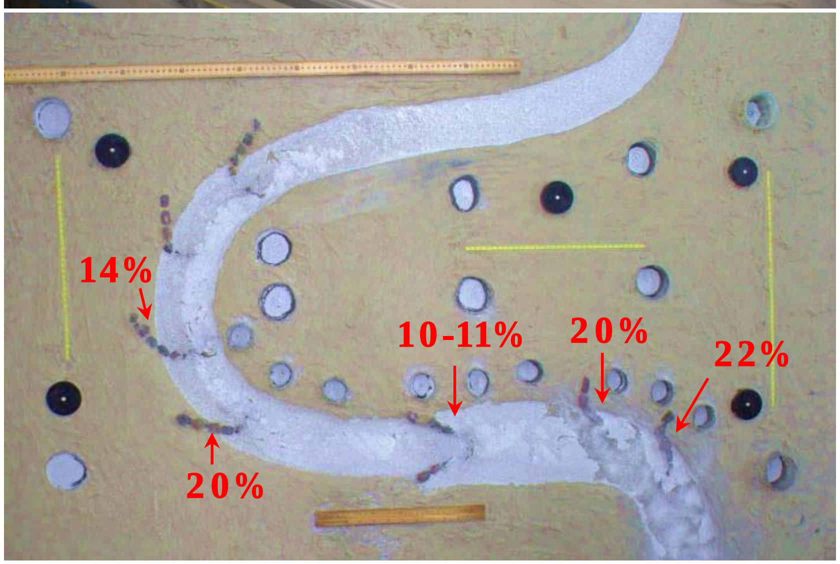
- **the hydraulic gradients in the stream channel and across the stream meander bend, and**
- **the intra-meander water table level?**

Use methodologies that will provide:

1) direct comparisons between channels with structures and channels without structures, and
2) fine resolution of observation data at the scale of a stream meander.

Methods: Laboratory Experiments





Stream Channel Dimensions:

- Width to Depth ratio: 7 to 11
- Sinuosity: 1.9 Radius of Curvature: 26 cm
- Channel slope: 1% Valley slope: 1.5%
- D_{50}: 0.2 mm $n_{no\ struct}$ = 0.004 n_{struct} = 0.021
- Initial channel: flat bed morphology

Experimental Runs:

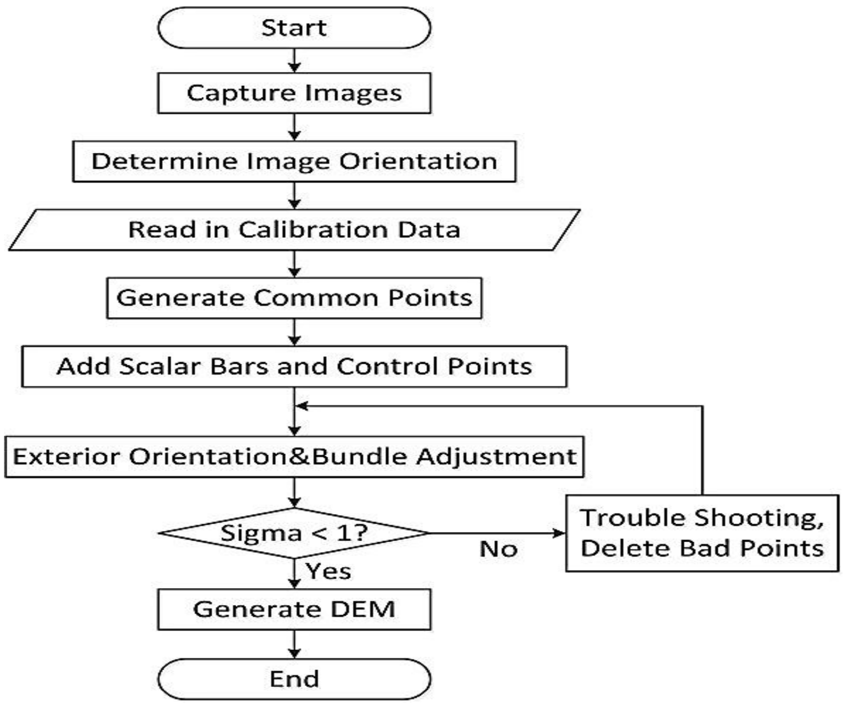
- Discharge: 51 ml/s (~30% of channel capacity)
- Flow Duration: 7 hr
- 3 replications of channel without structures
- 4 replications of channel with 6 J-hooks and 1 cross-vane

Close-Range Photogrammetry:

- 2 NIKON D5100 digital cameras mounted 1.3 m from sand surface
- Digital photos taken of initial channel, river stage at 7 hr of flow, and channel after 12+ hr of no flow
- Floating white wax powder (0.3 mm diameter) indicated river stage and well water level
- Elevation values referenced to 5 control points surveyed by ultrasonic distance sensors (0.2 mm precision)

Methods: Post-Processing

Using ADAM Tech 3DM Analyst:



(Diagram courtesy of Bangshuai Han)

Using ESRI ArcGIS:

Import DEMs in ArcGIS

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Convert DEMs into TINs

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Convert TINs into Rasters

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Obtain cross-section profiles with 3D Analyst extension

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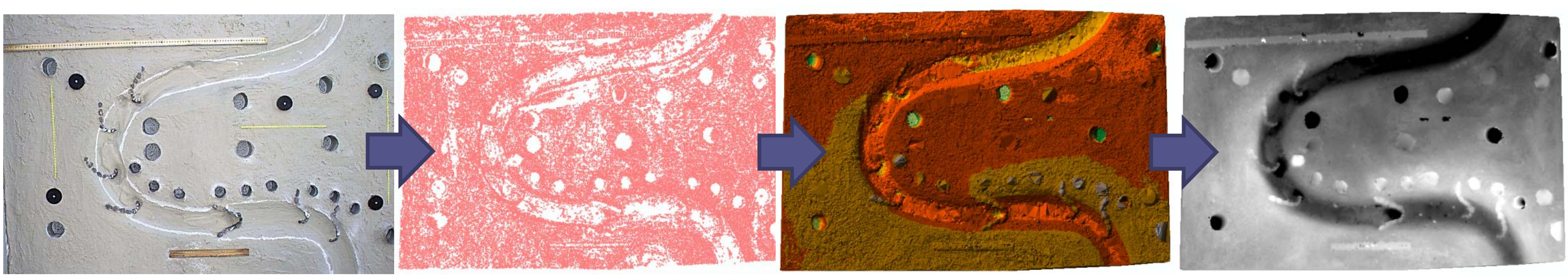
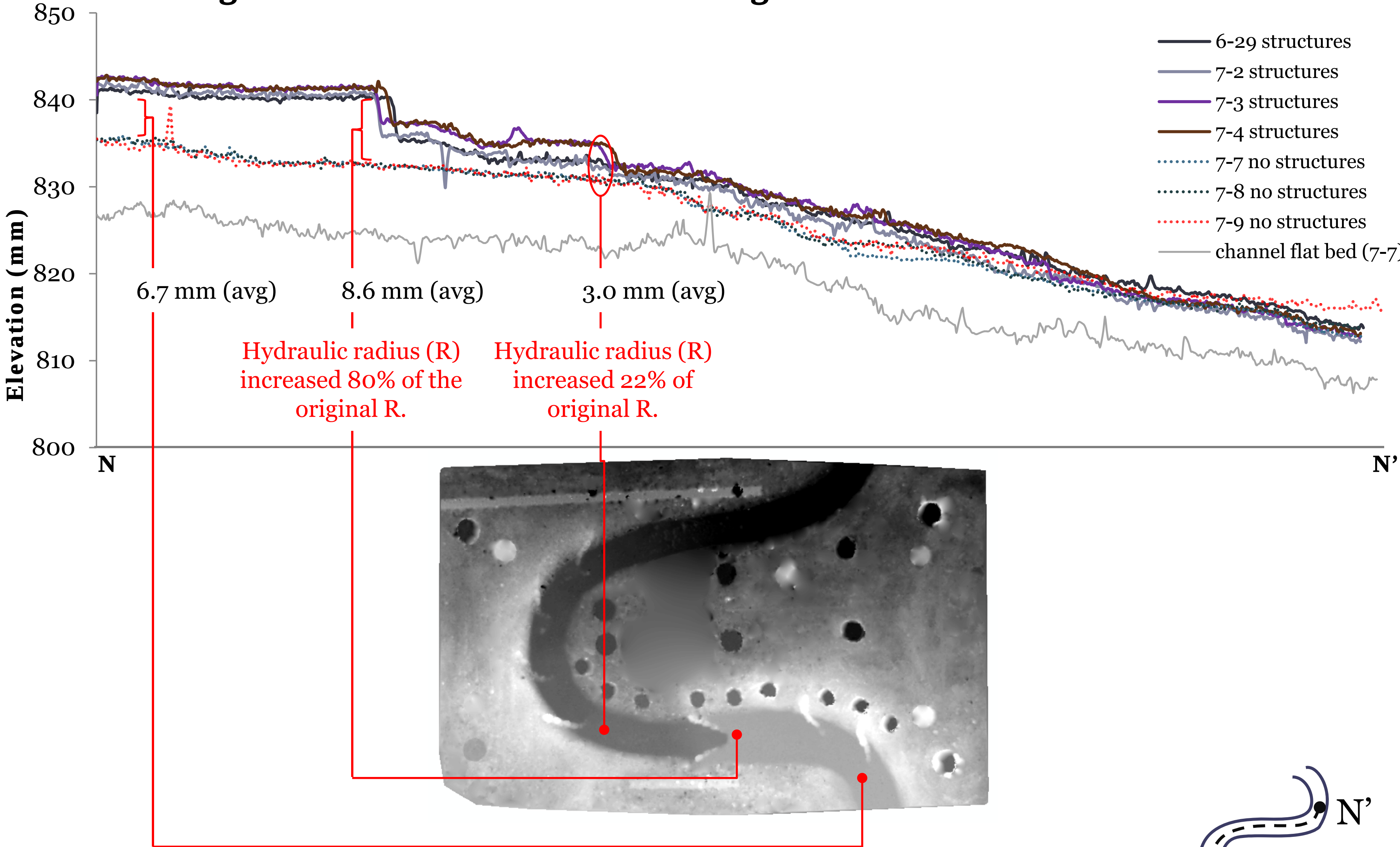
Export cross-section profile data into Excel for calculations

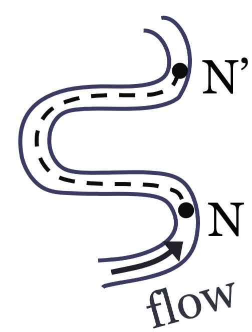
Analysis of variance on:

- Hydraulic gradients
- Water table levels



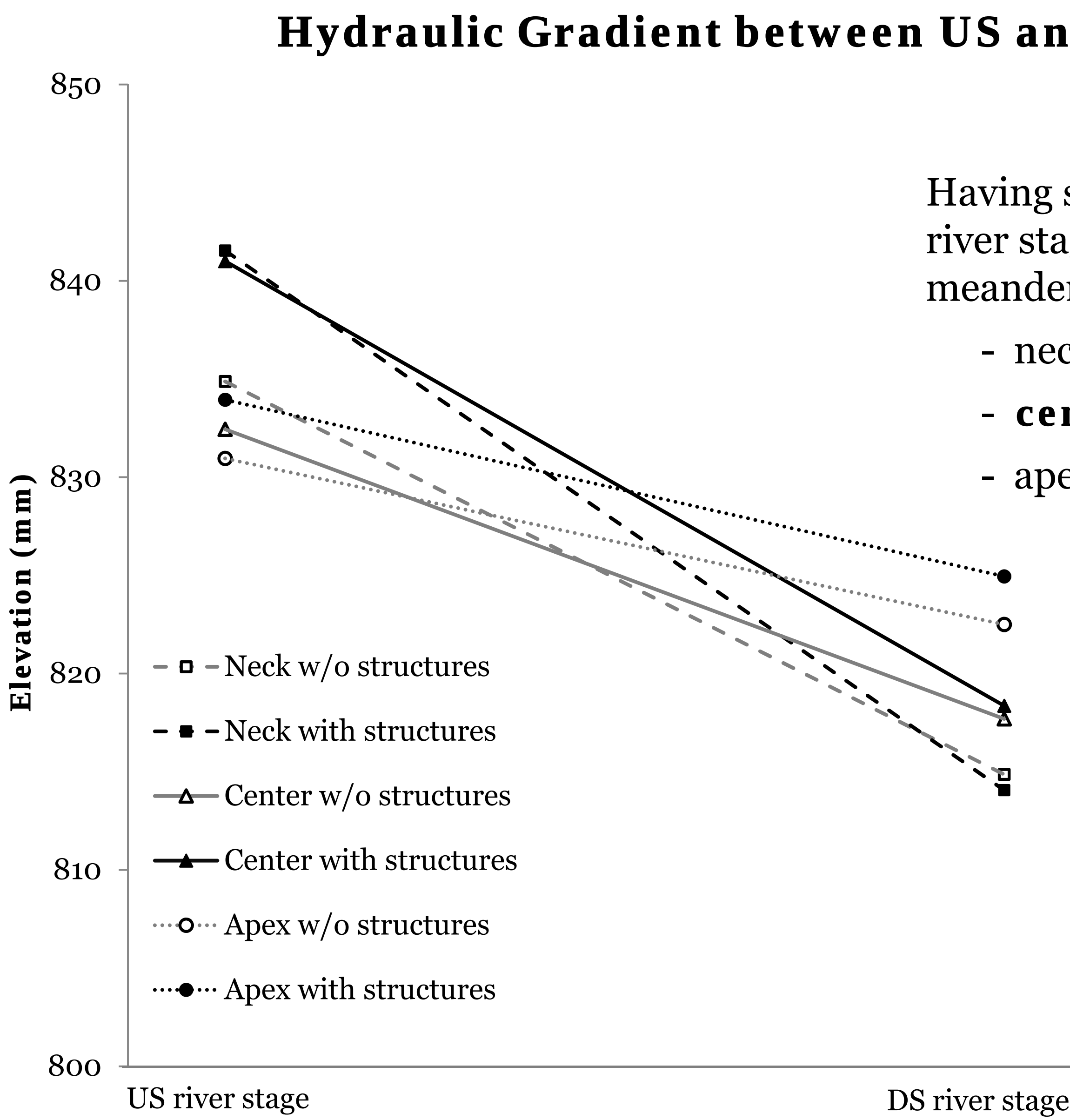
Longitudinal Profile of River Stage at the Channel Centerline





Having structures in the channel, especially the cross-vane, raised the river stage that is upstream of the structures.

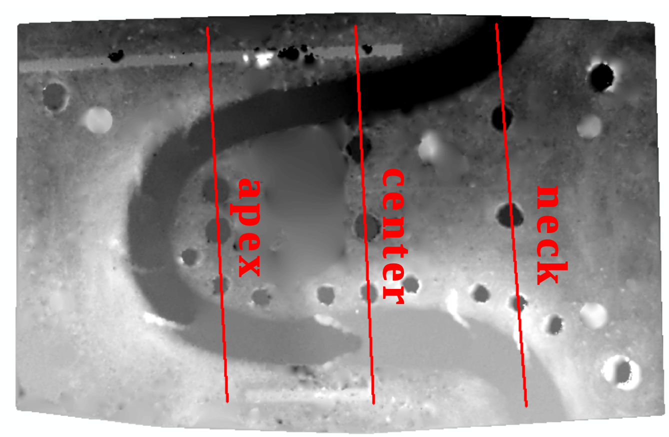
- Backwater from damming effect



Having structures in the channel raised the river stage hydraulic gradient across the meander:

- neck by 0.94%
- **center by 1.39%**
- apex by 0.12%

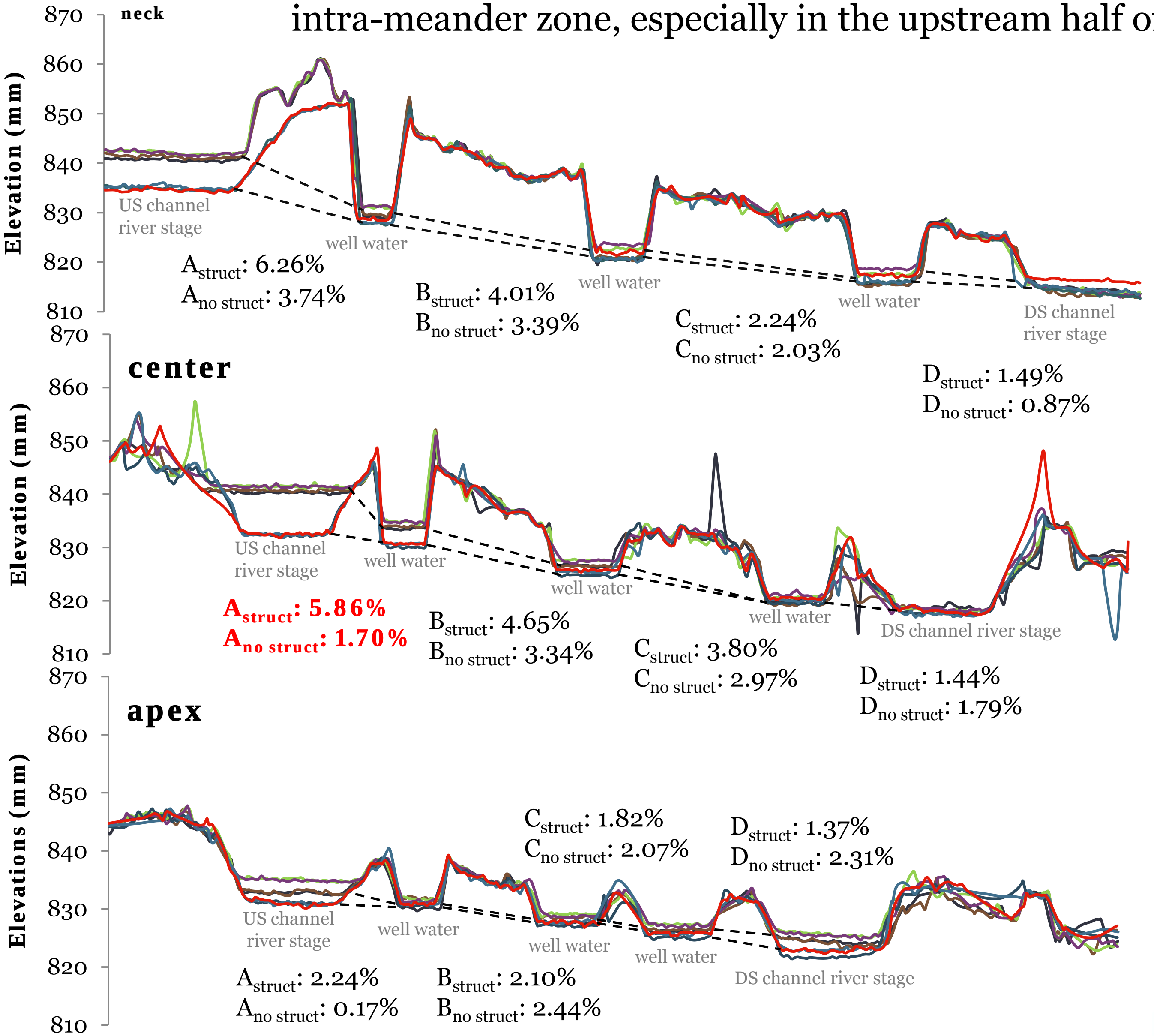
The river stage hydraulic gradients of channels with structures and those of channels without structures are statistically different (p=0.0002).



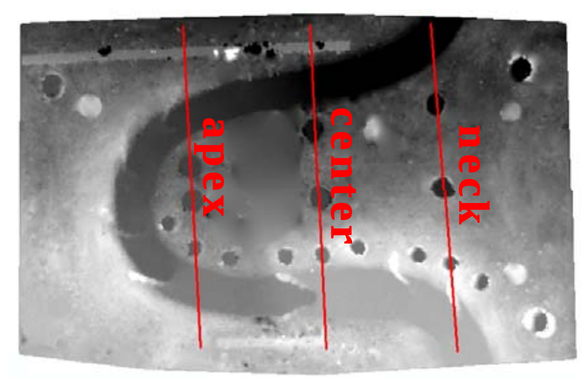
The structures affected the hydraulic gradient across the meander locations disproportionately (p<0.0001).

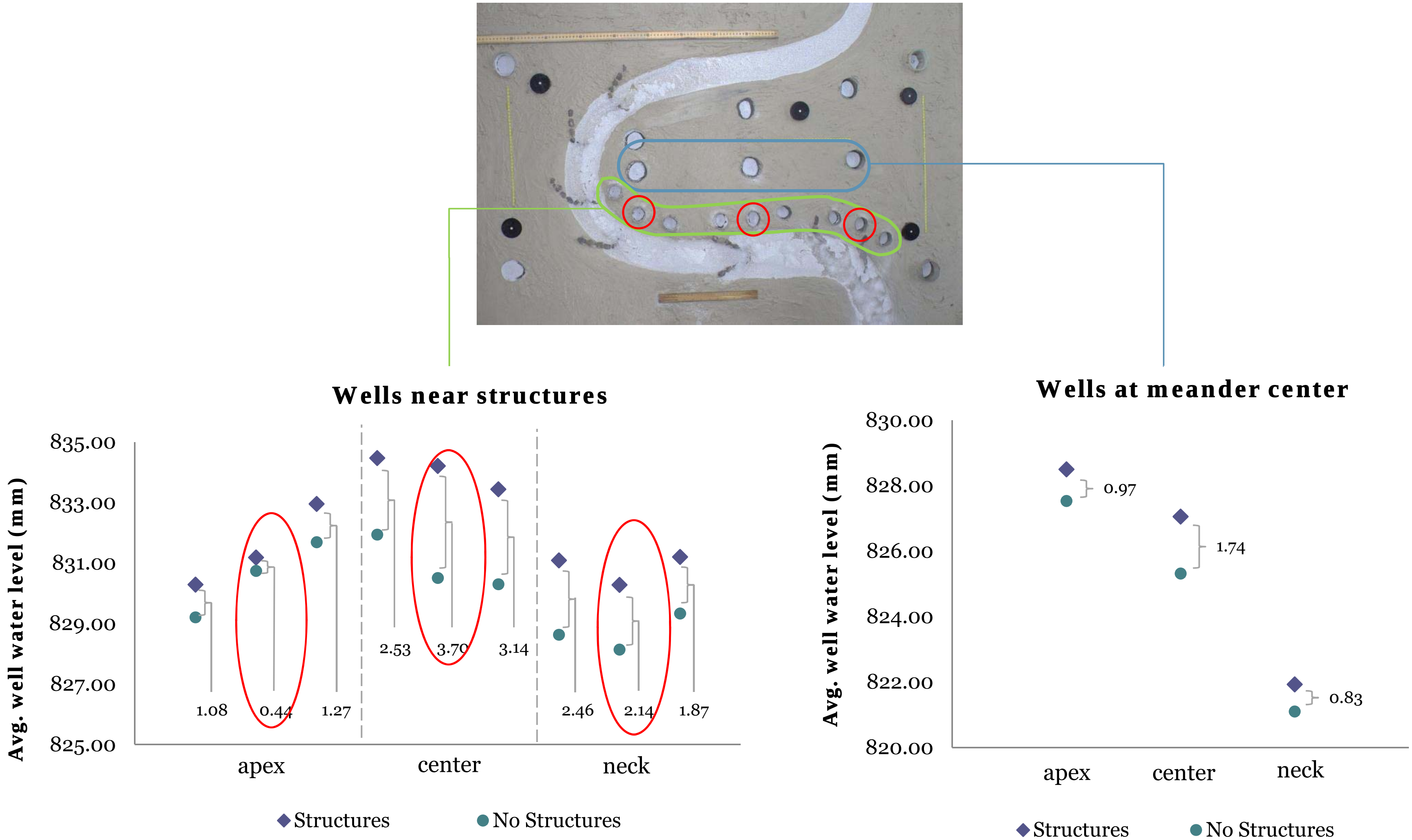
Intra-Meander Cross-Sections

Having structures in the channel increased the water table throughout the intra-meander zone, especially in the upstream half of the bend.



The steepest hydraulic gradient increase from in-channel structures occurred at the meander center, immediately upstream of cross-vane.





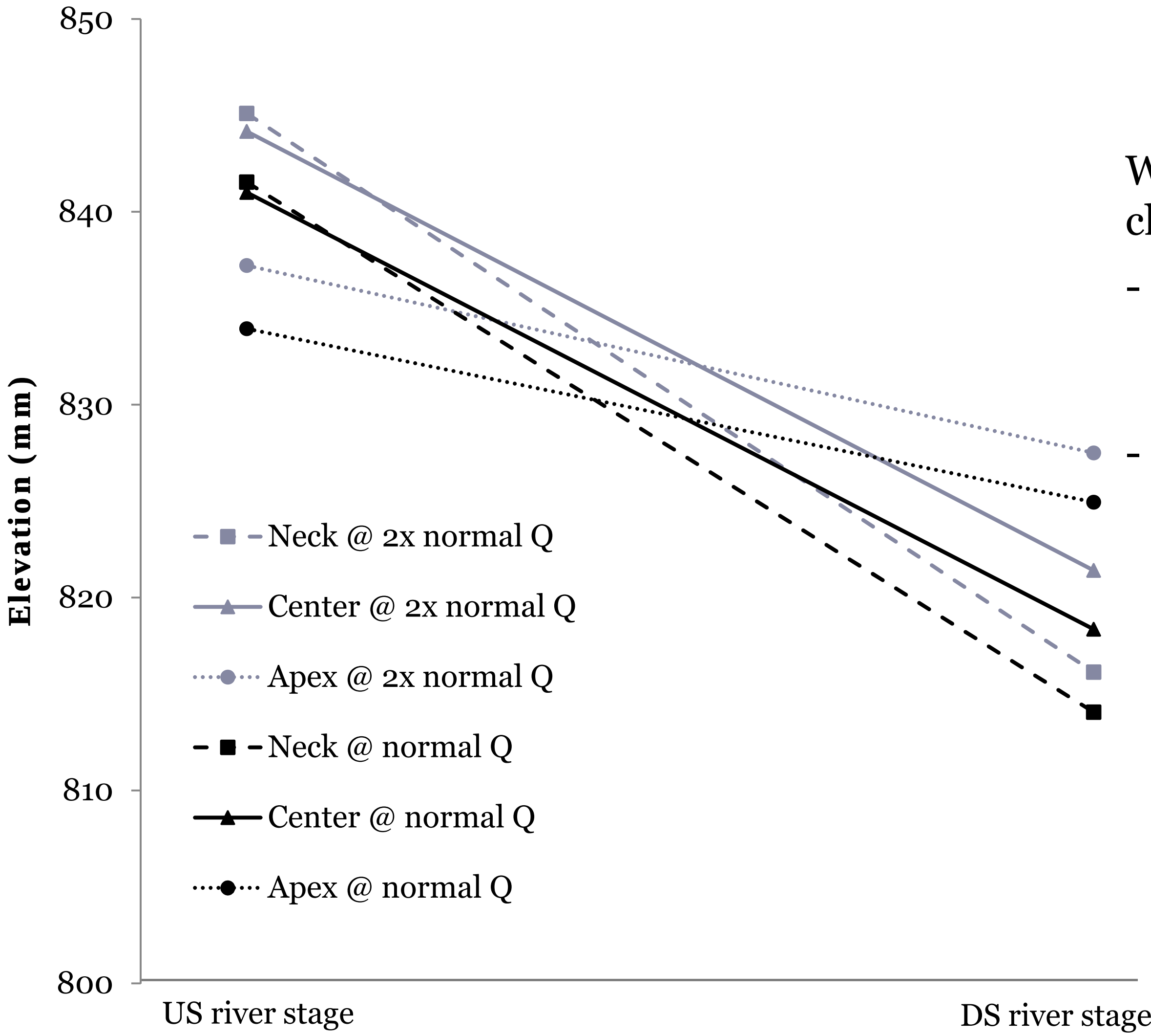
The water level of the circled wells was statistically different:
- between channels with structures and those without structures ($p=0.0057$), and
- across meander locations (neck, center, apex) ($p<0.0001$).

The structures impacted these wells' water level disproportionately across meander locations ($p=0.0001$)

The water level of these wells was:
- marginally different between channels with structures and those without structures ($p=0.0797$), and
- statistically different across meander locations ($p<0.0001$).

The structures did NOT impact these well water levels disproportionately across meander locations ($p=0.2889$).

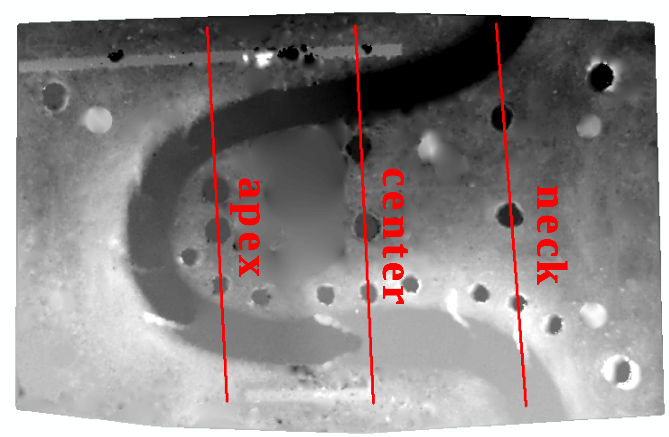
Hydraulic Gradient between US and DS River Stage during twice normal discharge



When discharge was doubled in channels with structures:

- river stage increased with similar magnitude throughout the channel, and
- hydraulic gradients across the meander bend remained relatively unchanged.

Normal Q = 51 ml/s



Result Summary

- In-stream restoration structures can locally raise the river stage upstream of where they are installed.
  - Cross-vanes can cause more backwater than J-hooks.
- The increase of intra-meander hydraulic gradients and water table levels by in-channel stream restoration structures is most pronounced at the intra-meander areas closest to the structures.
  - There is marginal water table level increase in the middle of the meander bend.
- The structures do not appear to further increase hydraulic gradients under higher stream flow.

Implications on Hyporheic Exchange

- Steep hydraulic gradients in riparian areas closest to the structures could indicate areas of induced lateral hyporheic exchange.
  - Potential biogeochemical hotspots in the intra-meander zones.
- Larger stream flow in channels with restoration structures could induce more vertical hyporheic exchange due to higher hydraulic head.

Future Research

- More laboratory experiments to obtain observation data on hyporheic exchange flux and pathways in the stream channel and intra-meander zone.
  - Run experiments at different stream discharges and channel restoration designs.
- MODFLOW modeling to simulate and predict hyporheic exchange flux and pathways.
  - DEMs generated by our research process can provide fine resolution observation data of ground and water surfaces as MODFLOW boundary conditions.

Questions?

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