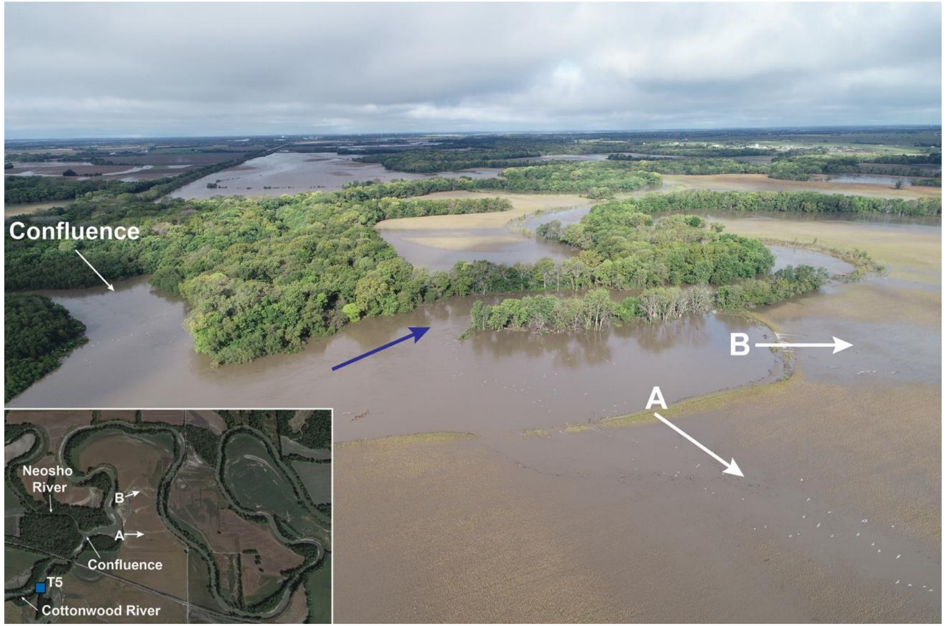
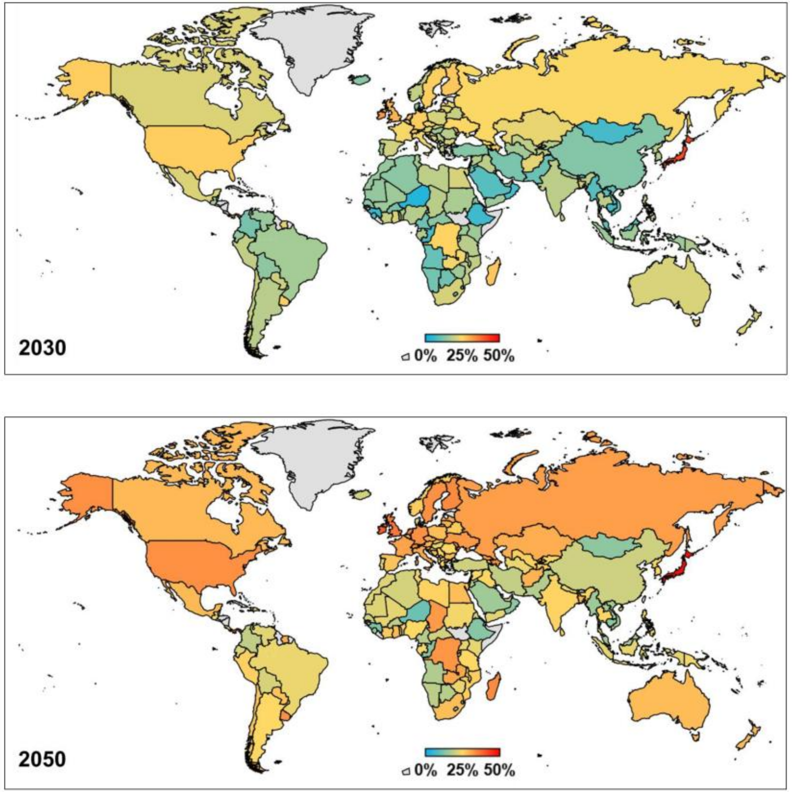
Reservoir sedimentation: Watershed and lake management solutions



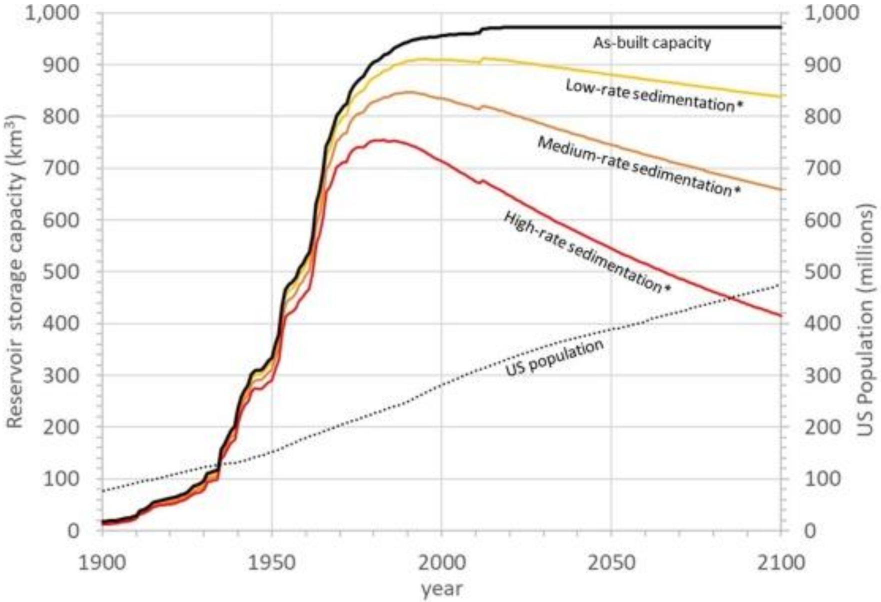
KANSAS GEOLOGICAL SURVEY
The University of Kansas

Tony Layzell, Kansas Geological Survey

Reservoir sedimentation - A significant global problem



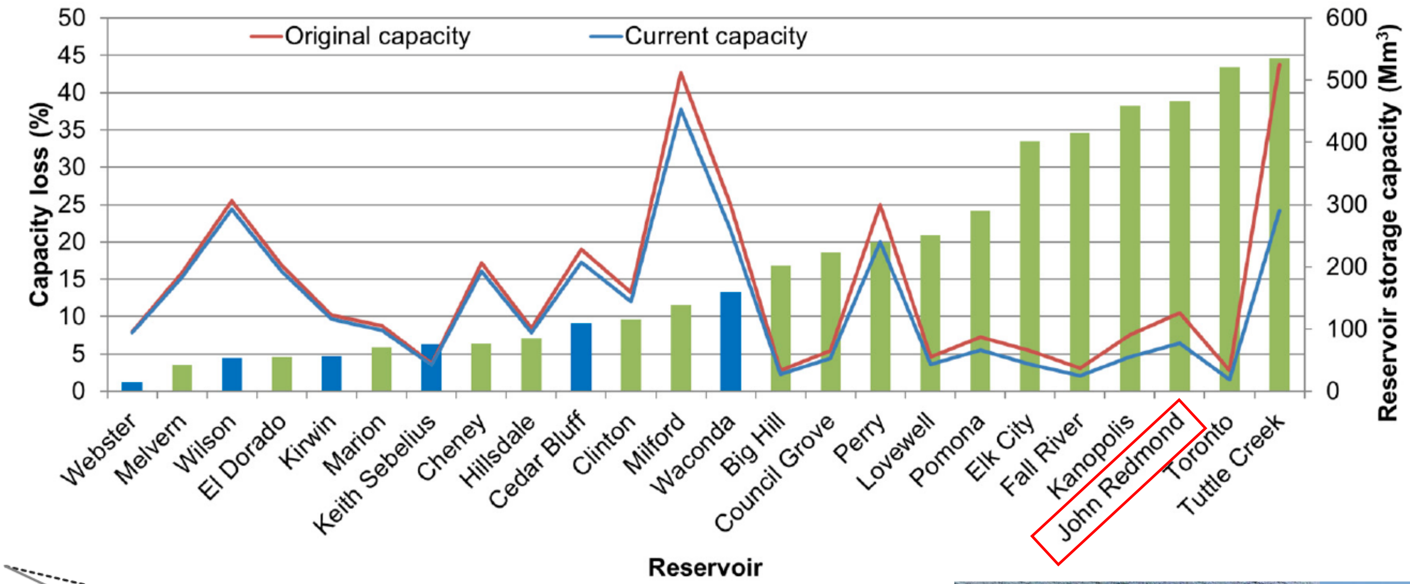
Estimated storage loss (%) (Perera et al., 2023)

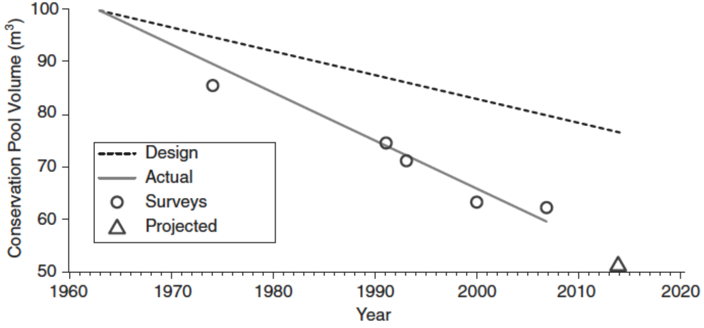


Storage capacity loss, United States (Randle et al., 2019)

Reservoir sedimentation in Kansas

Rahmani et al., 2018



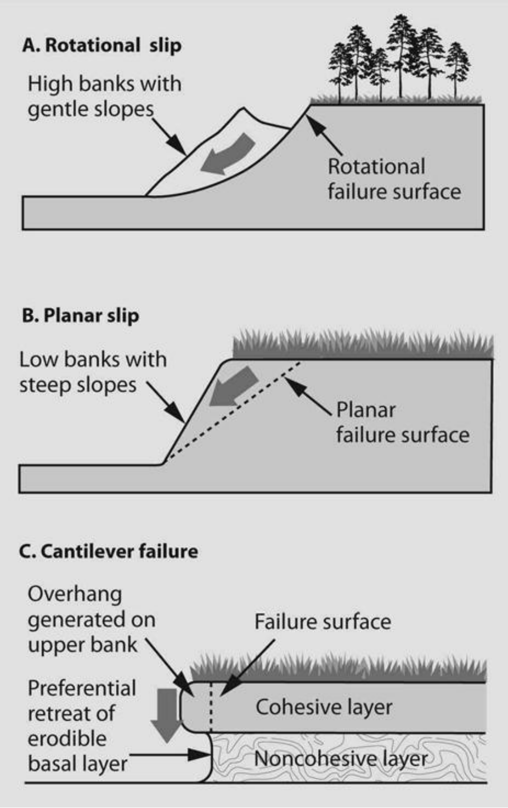


Podolak and Doyle, 2015

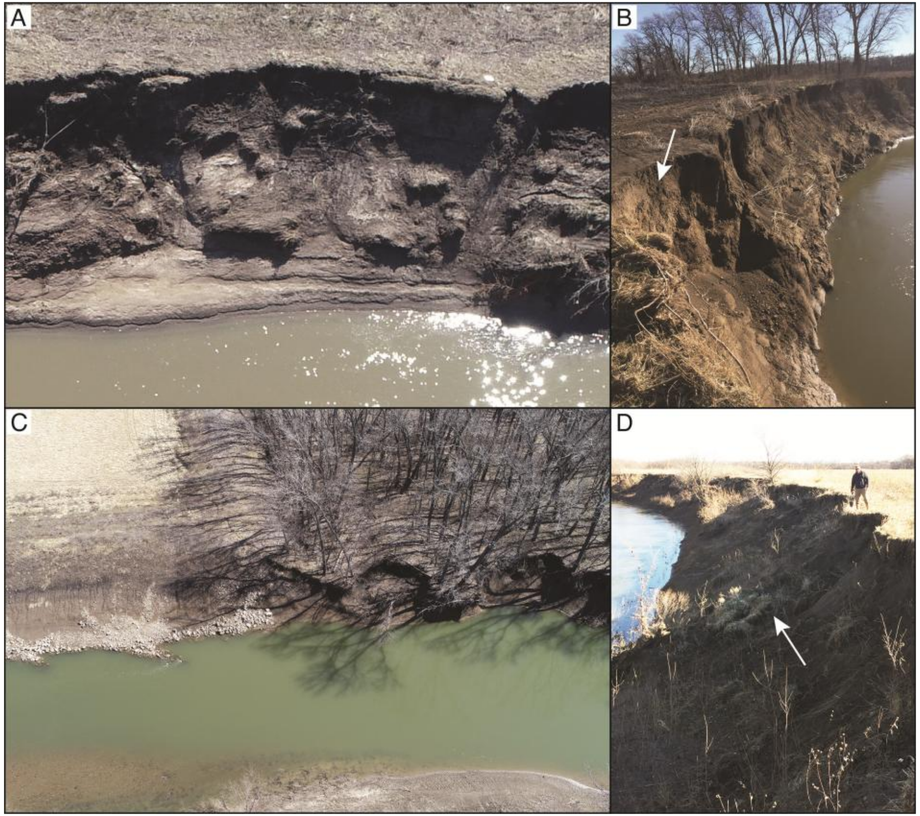
- \$20 million dredging operation in 2016
- 2.3 million m^3 removed

The problem

Where does the sediment come from?



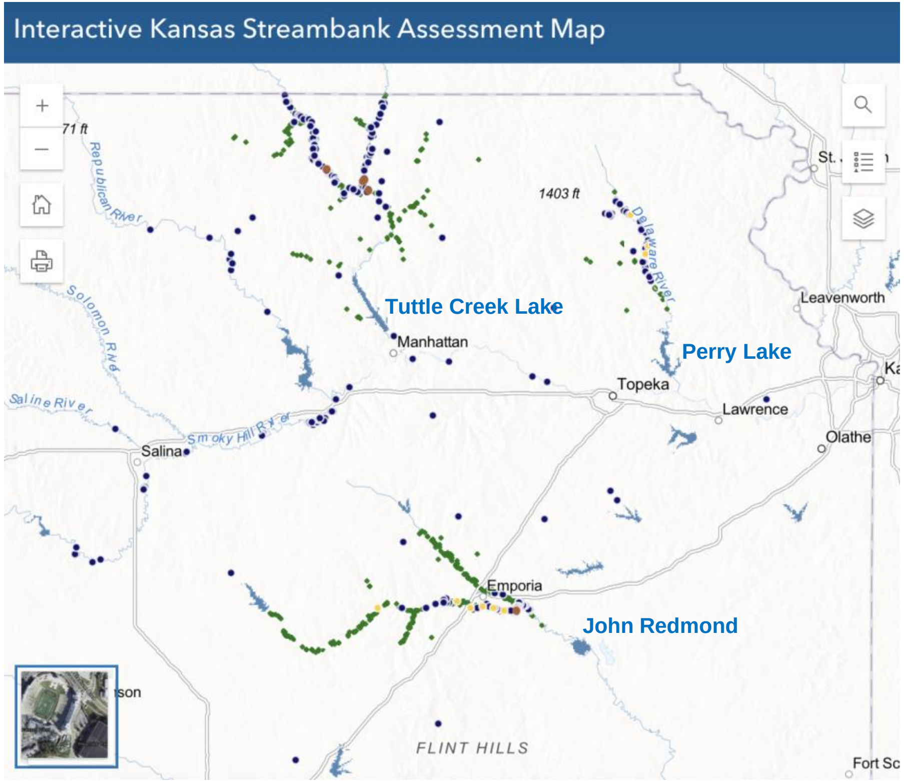
Thorne, 1978

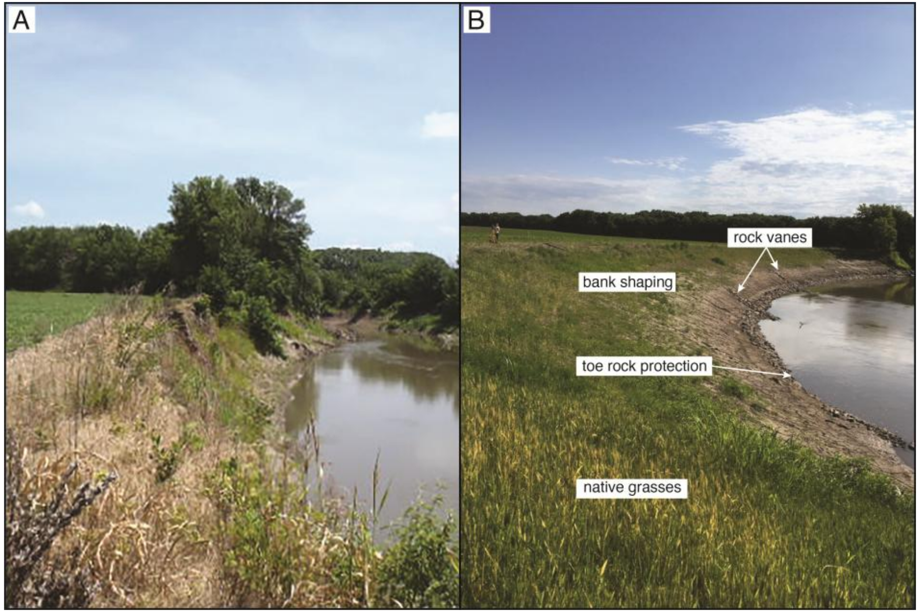


Layzell et al., 2022

The solution (?)

Streambank stabilization (upstream)





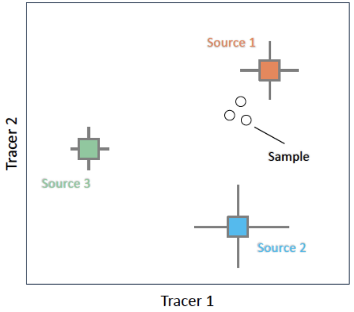
Do these stabilization efforts work?

A question of scale

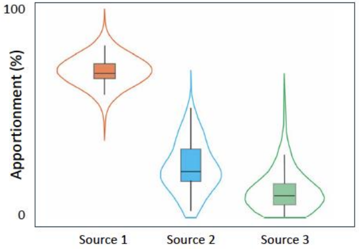
Test assumptions

Watershed scale

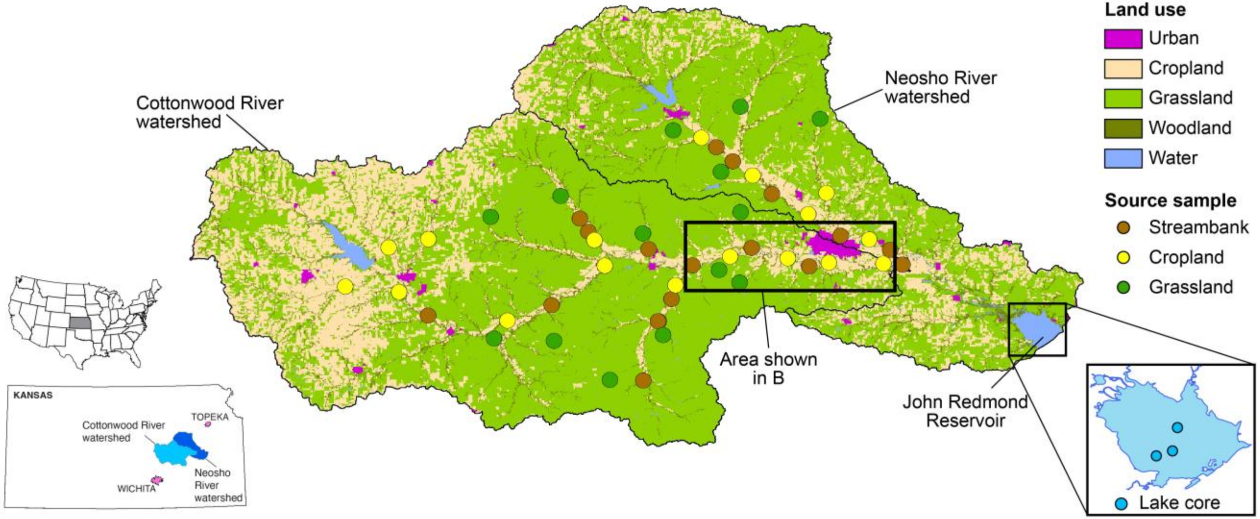
- Where does the sediment infilling John Redmond Reservoir come from?
- Sediment fingerprinting - a modeling tool that can “unmix” a composite sediment sample into its constituent source fractions



Numerous tracers - PCA

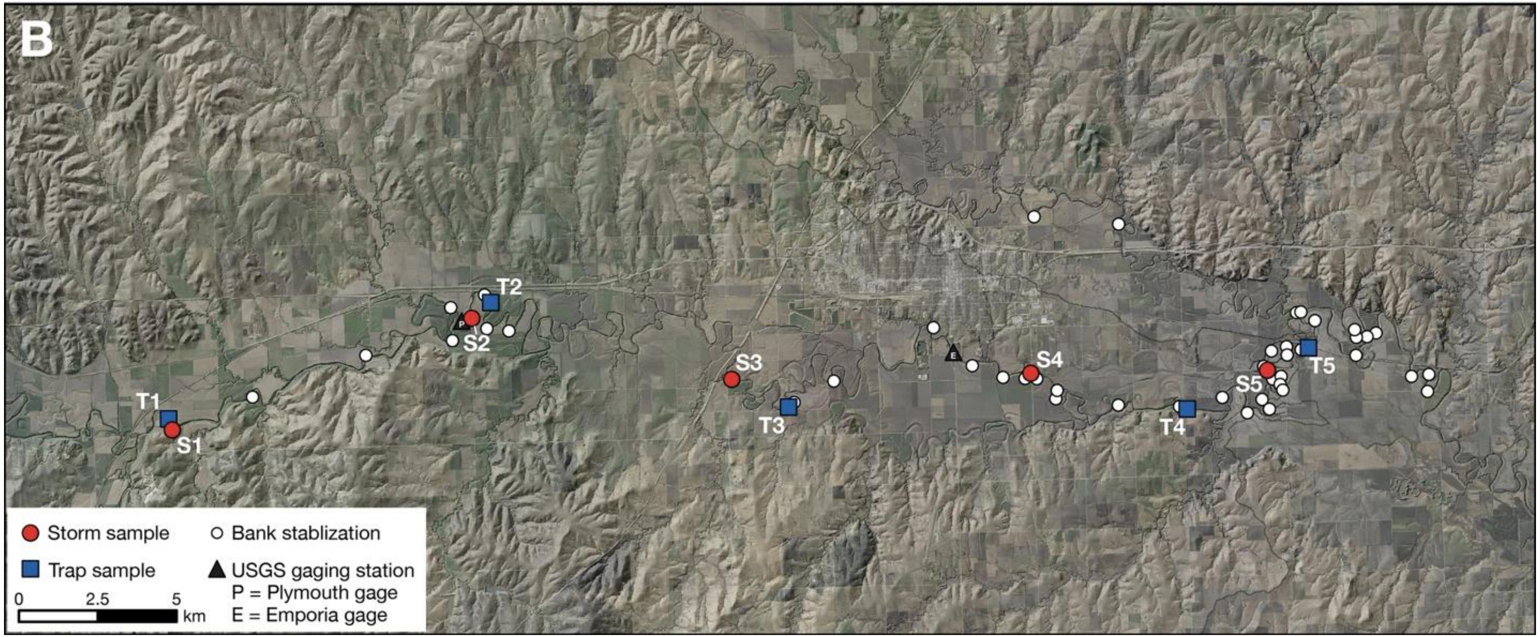


Bayesian modeling

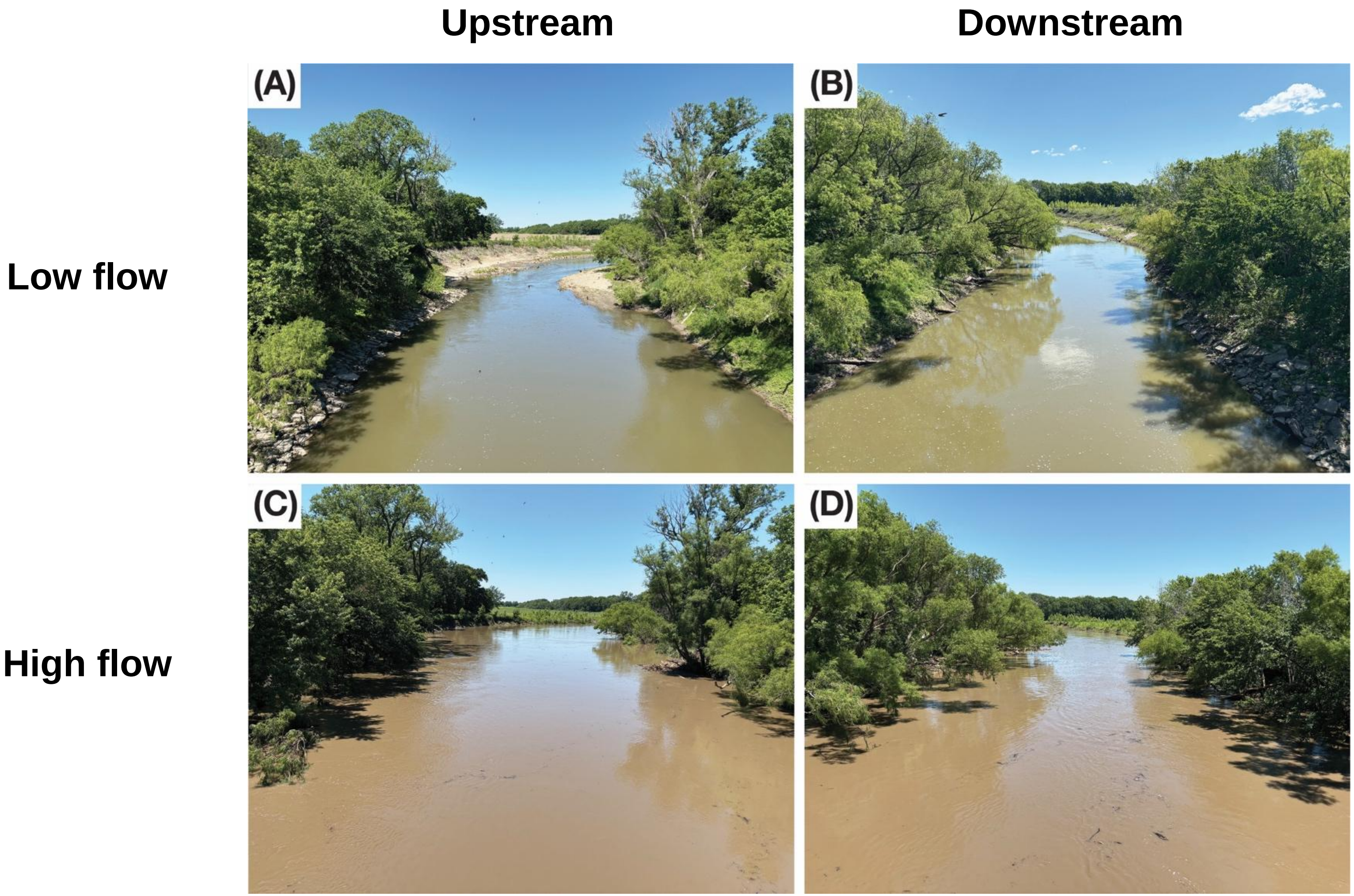


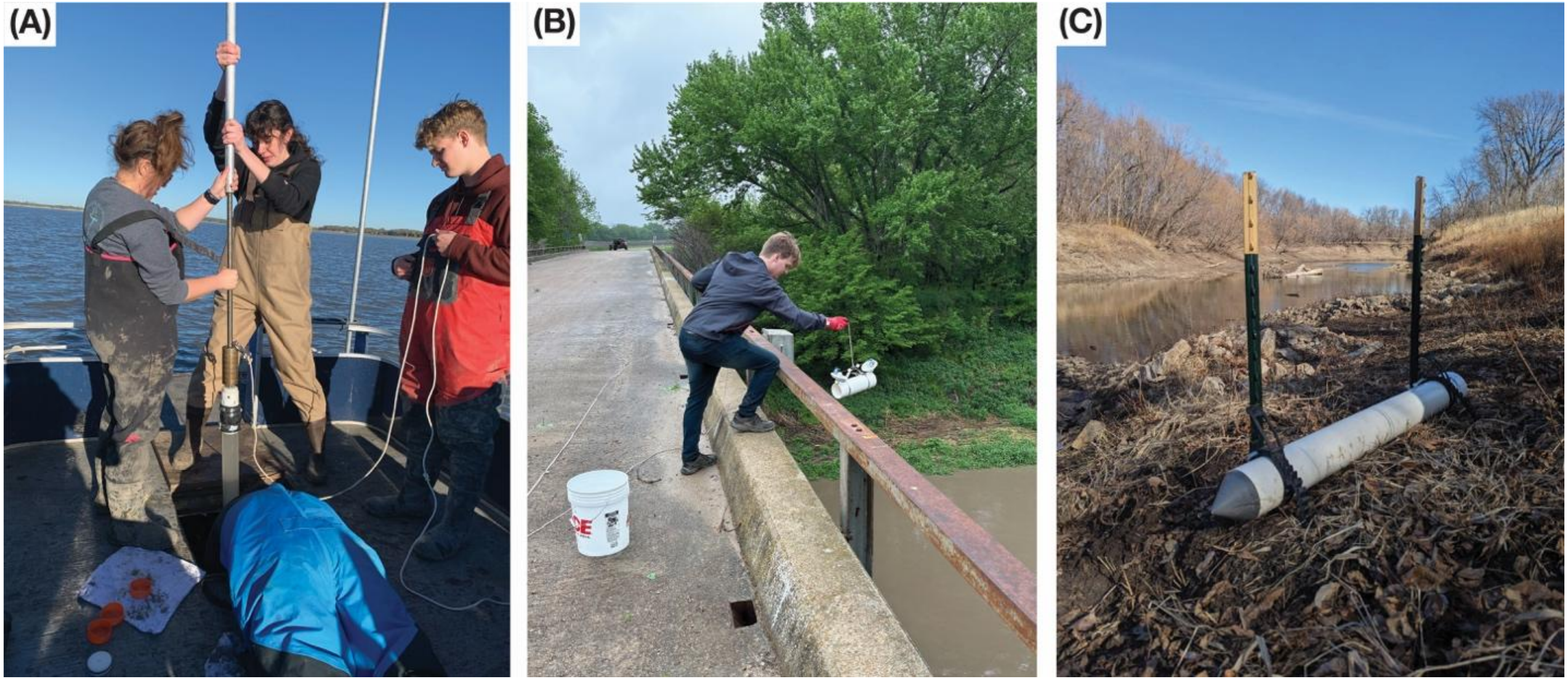
Watershed scale

- Where does the sediment in the Cottonwood River come from?

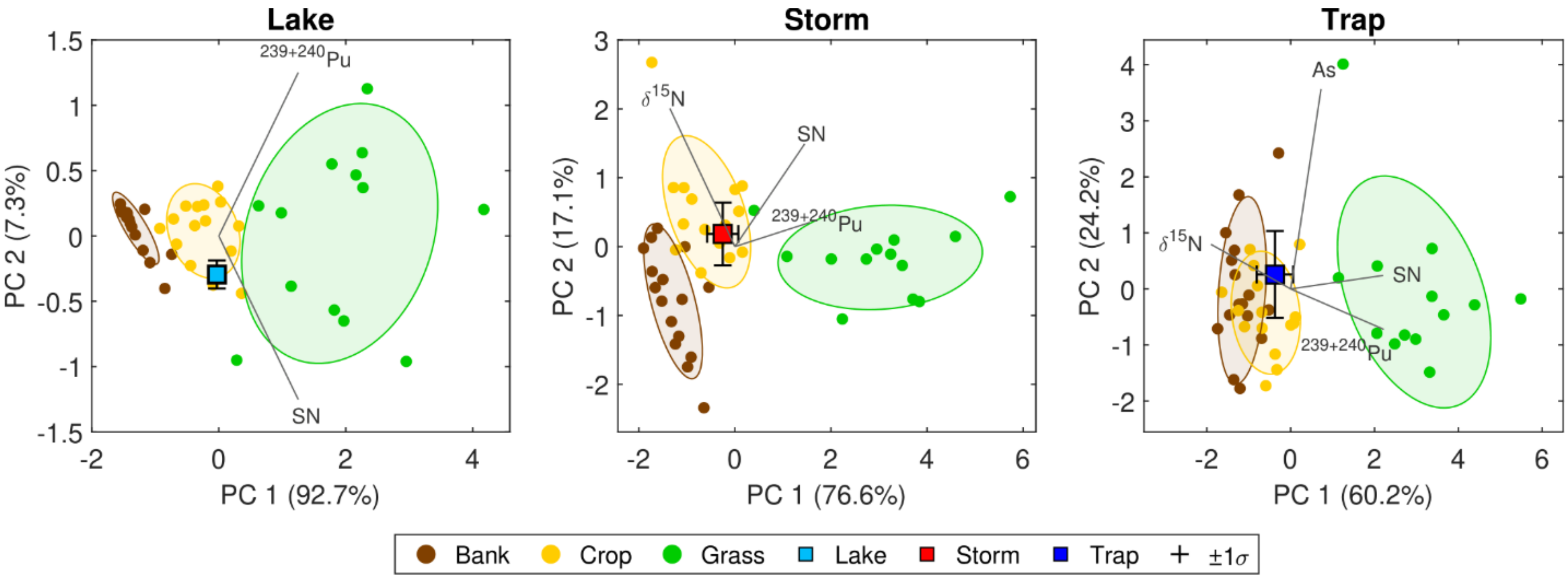


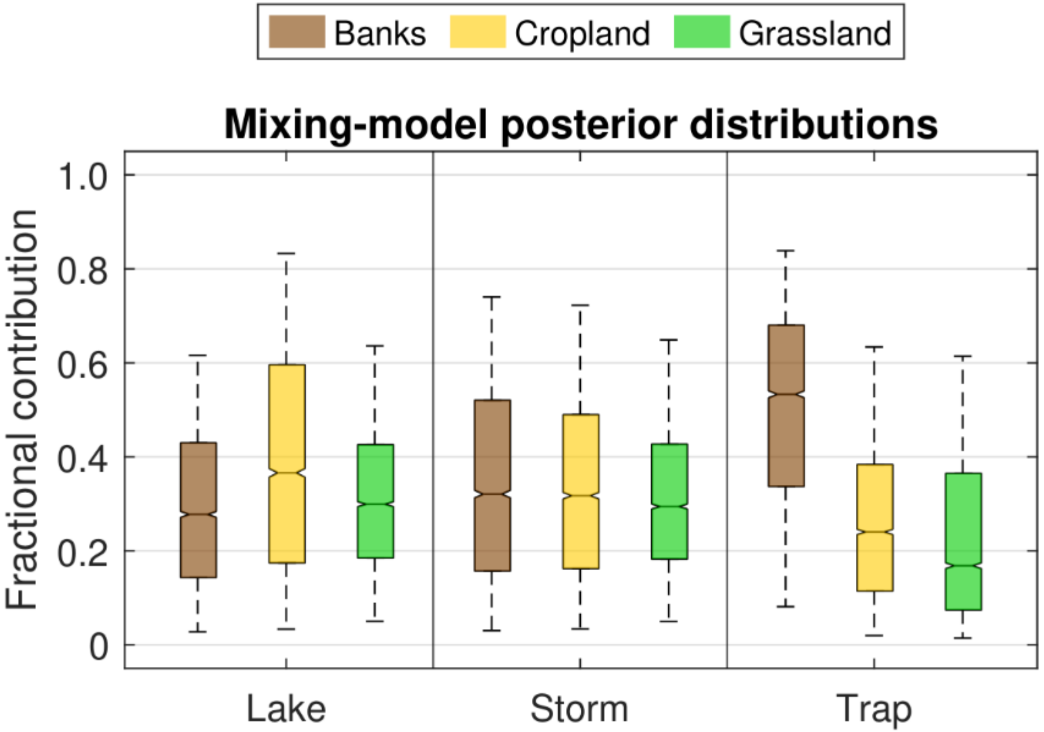
- Assess the utility of sediment fingerprinting to inform on the efficacy of streambank stabilization projects in reducing sediment loads at the watershed scale.


Upstream
Downstream
Low flow
High flow
(A)
(B)
(C)
(D)


(A)
(B)
(C)

Sediment fingerprinting – 29 tracers (organics, geochemical, radioactive isotope)





Lakebed

29% Bank

40% Cropland

31% Grassland

Storm

35% Bank

34% Cropland

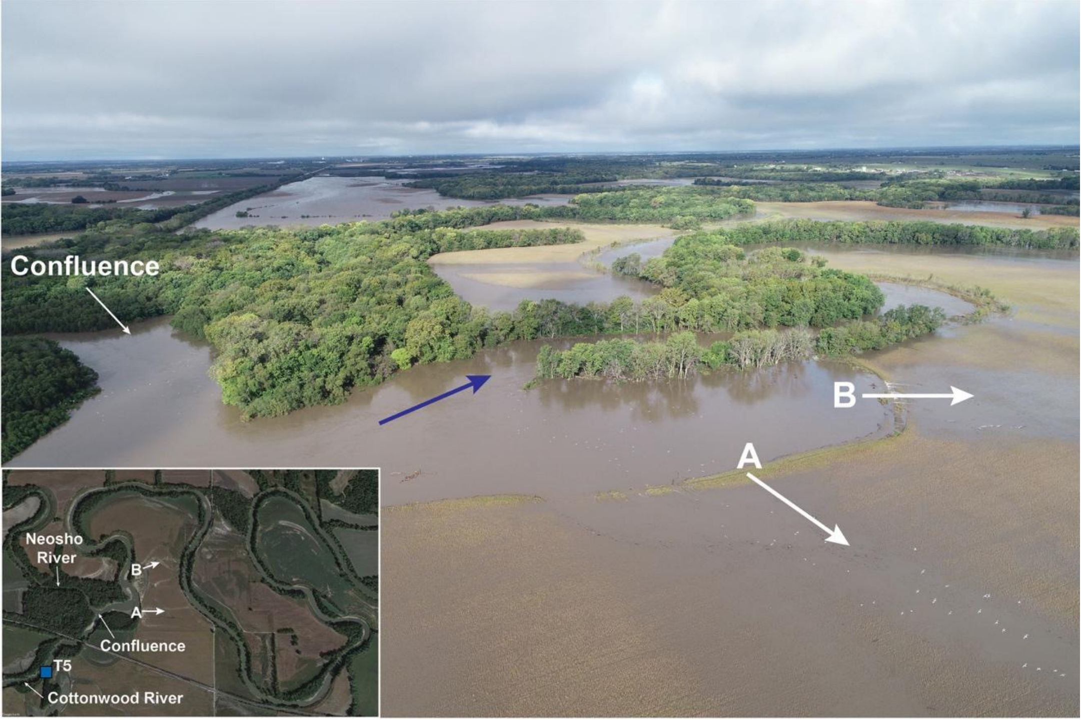
31% Grassland

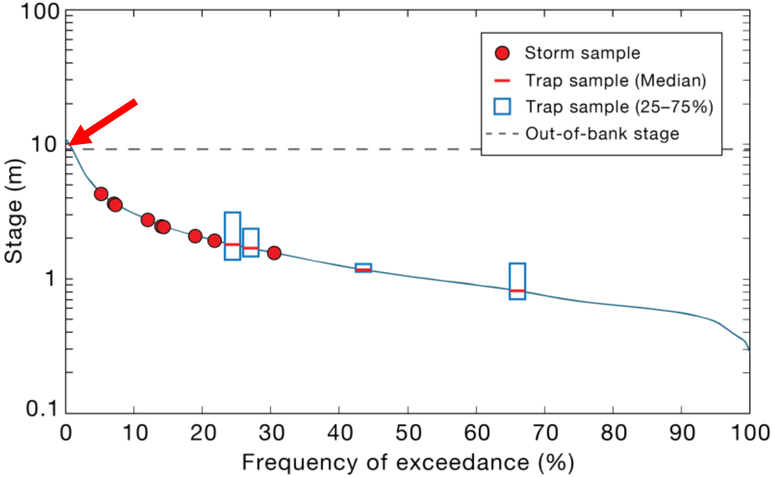
Trap

50% Bank

27% Cropland

23% Grassland

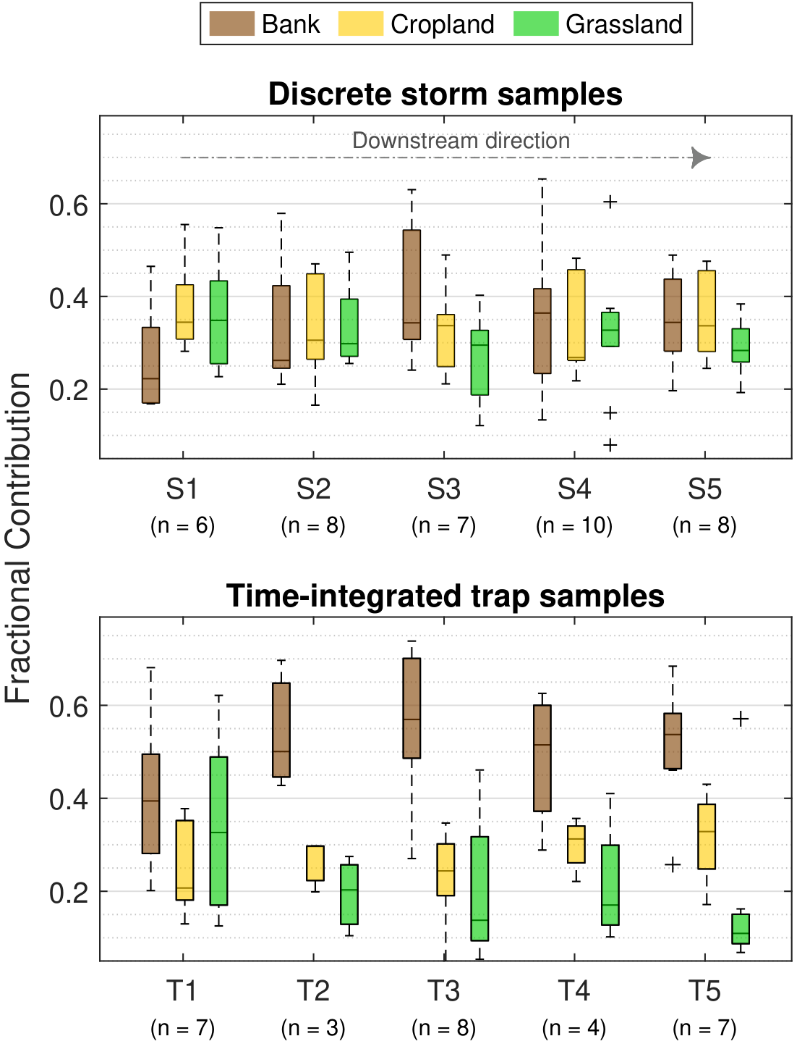




- Disproportionally large sediment loads occur during high-magnitude flood events.
- Total suspended-sediment load transported by **out-of-bank** flood events (2016–2019):
  - Plymouth gage = 48%
  - Neosho Rapids gage = 78%

S1 = 28% ➡ **S5 = 35%**

T1 = 41% ➡ **T5 = 50%**



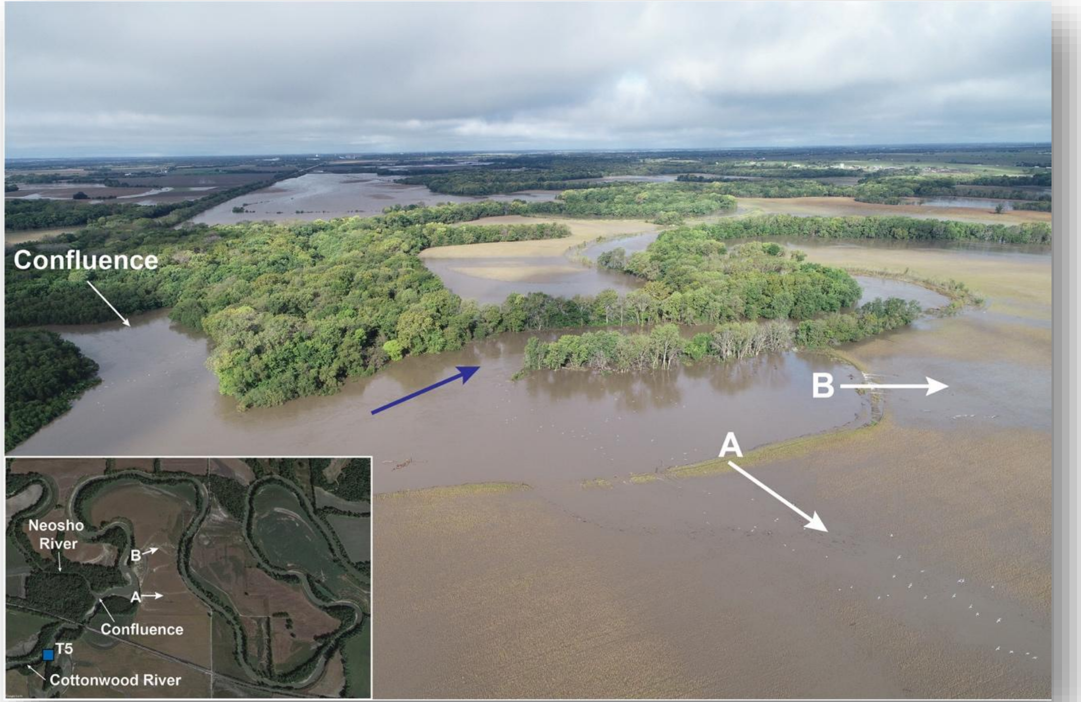
Increase in bank erosion along the study reach, despite the implementation of numerous stabilization projects.

BUT no counterfactual scenario.

Highlights the importance of baseline data.

Sediment sources

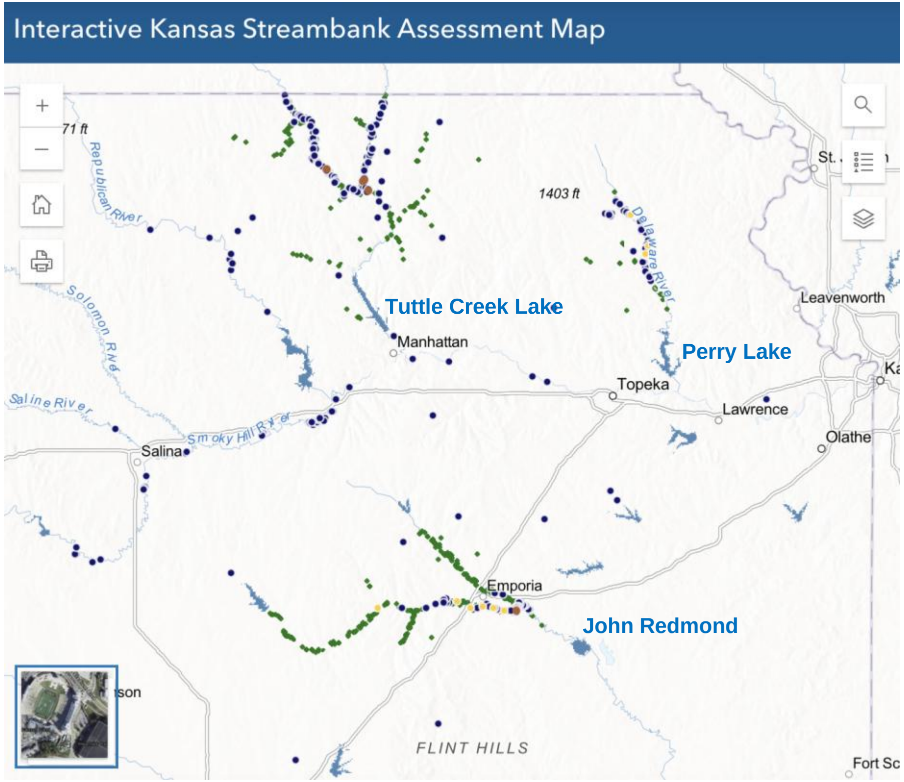
- Sediment infilling John Redmond Reservoir is predominantly from cropland sources not streambanks.
- Disproportionally large sediment loads occur during high-magnitude out-of-bank flood events.
- Targeted management should include not only streambank stabilization, but also practices aimed at reducing upland erosion, particularly cropland.



- Currently studying sediment sources in 16 other reservoir watersheds

The solution (?)

Water Injection Dredging (in lake)

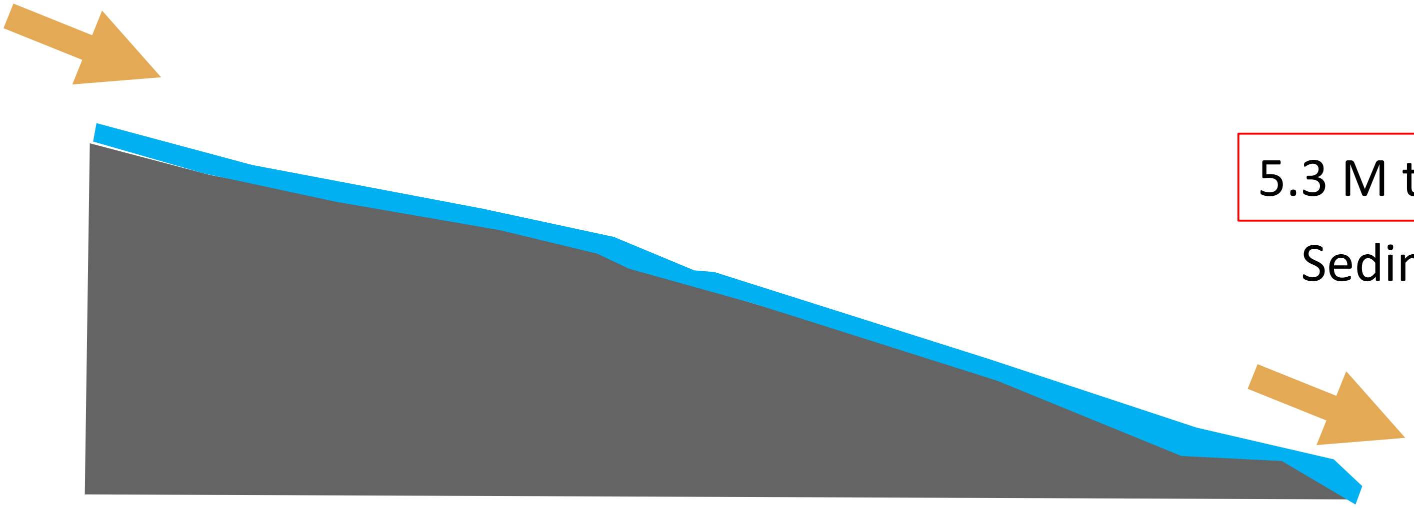


Thanks to John Shelley (KU)!

Big Blue River

5.3 M tons/year

Sediment
In

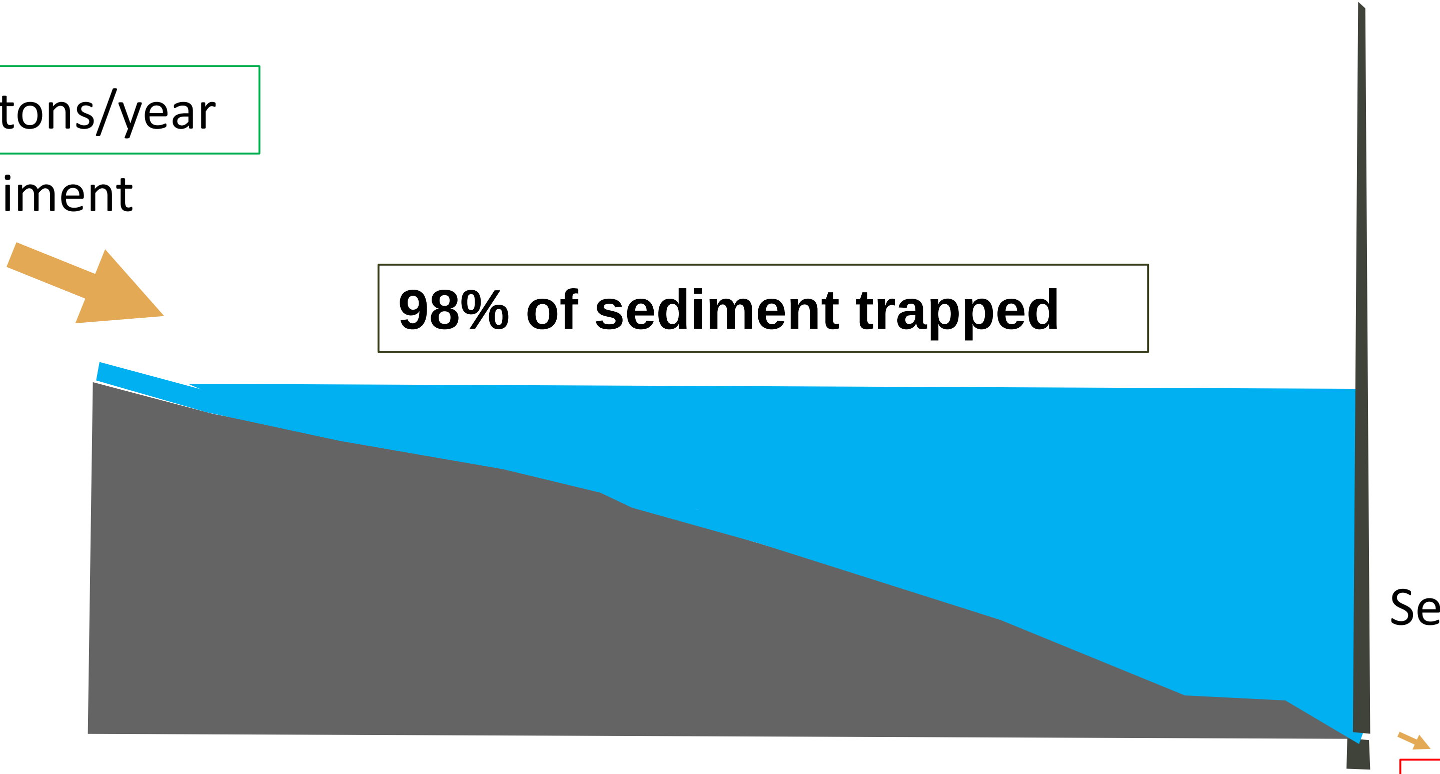


5.3 M tons/year

Sediment Out

Slide Credit: John Shelly, KU CEAE

Tuttle Creek Lake



5.3 M tons/year

Sediment In

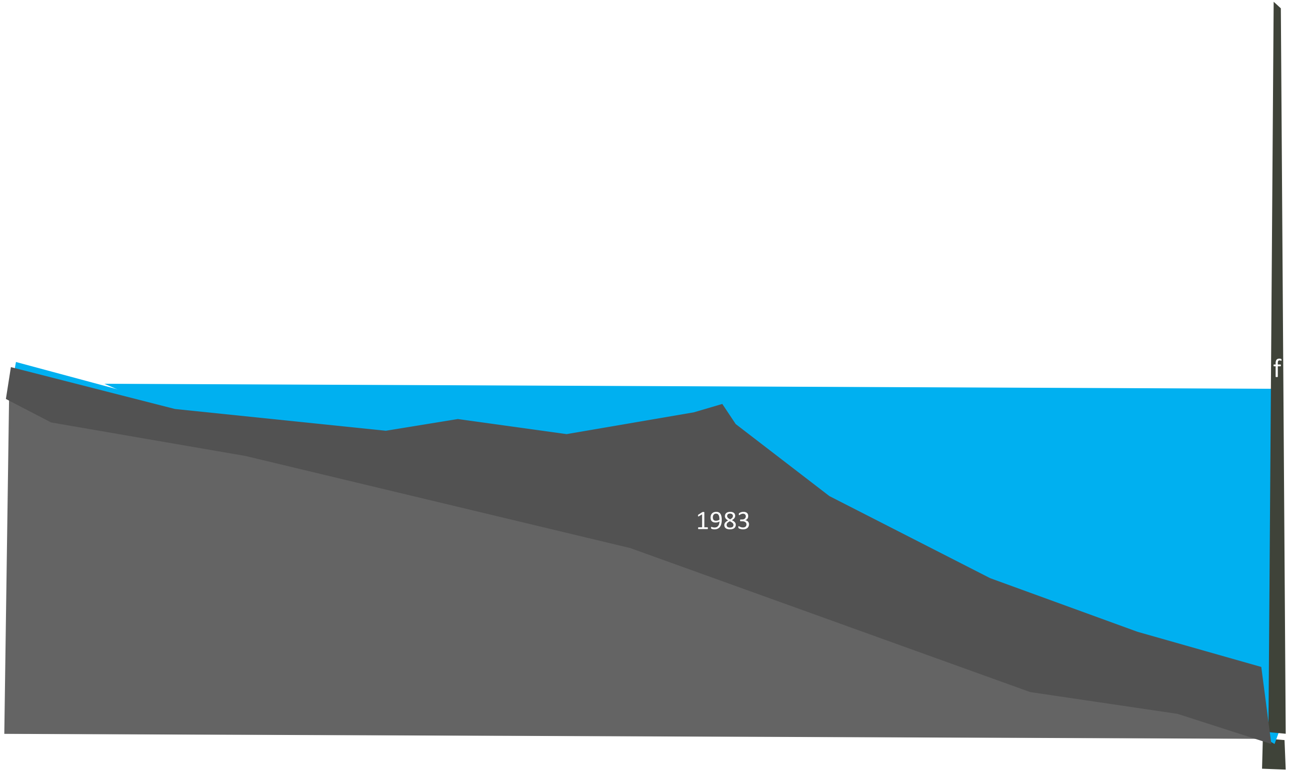
98% of sediment trapped

Sediment Out

107k tons/year

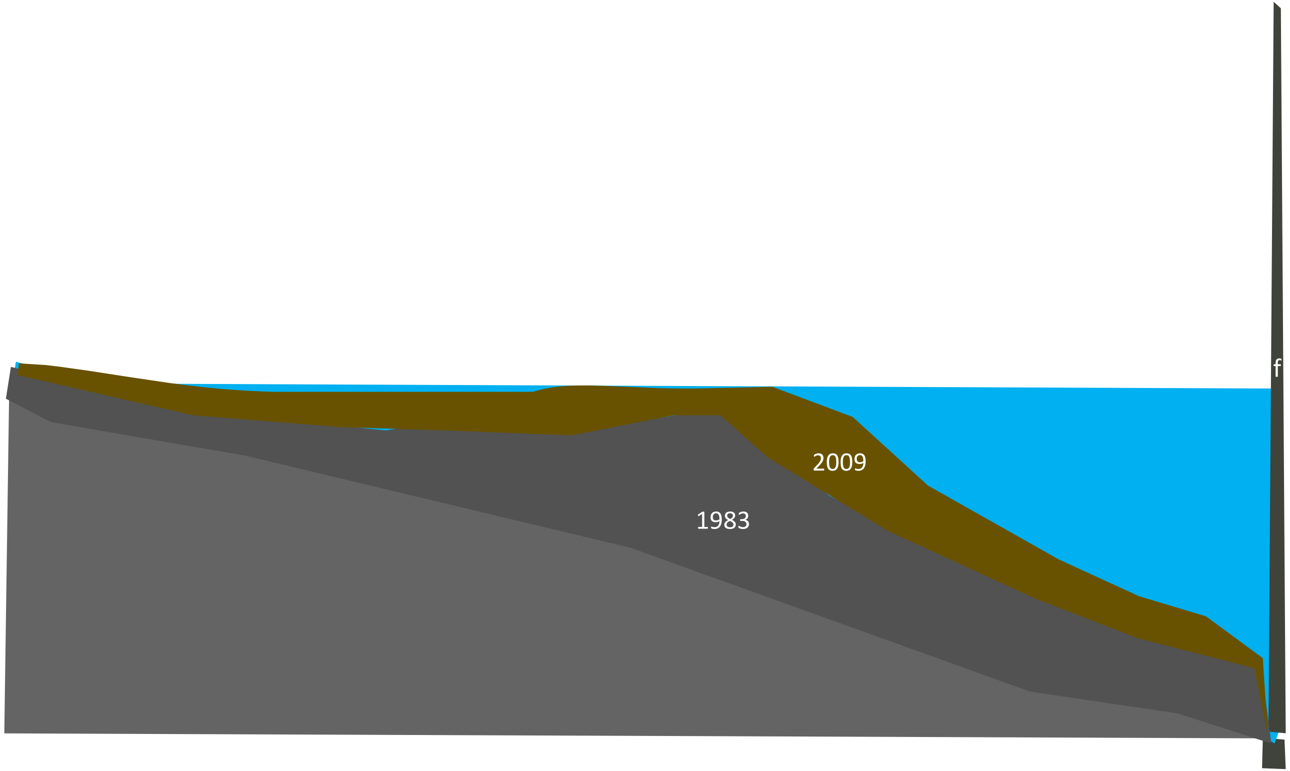
Slide Credit: John Shelly, KU CEAE

Tuttle Creek Lake



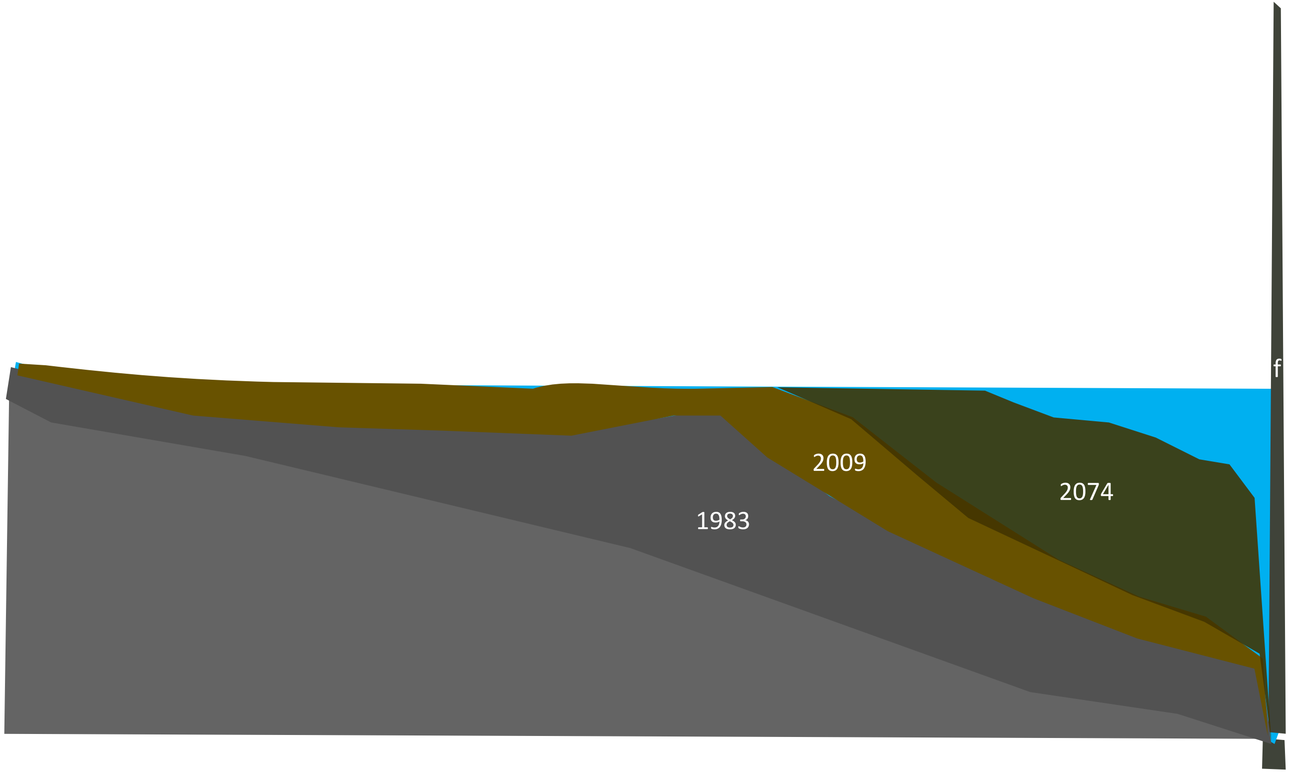
Slide Credit: John Shelly, KU CEAE

Tuttle Creek Lake



Slide Credit: John Shelly, KU CEAE

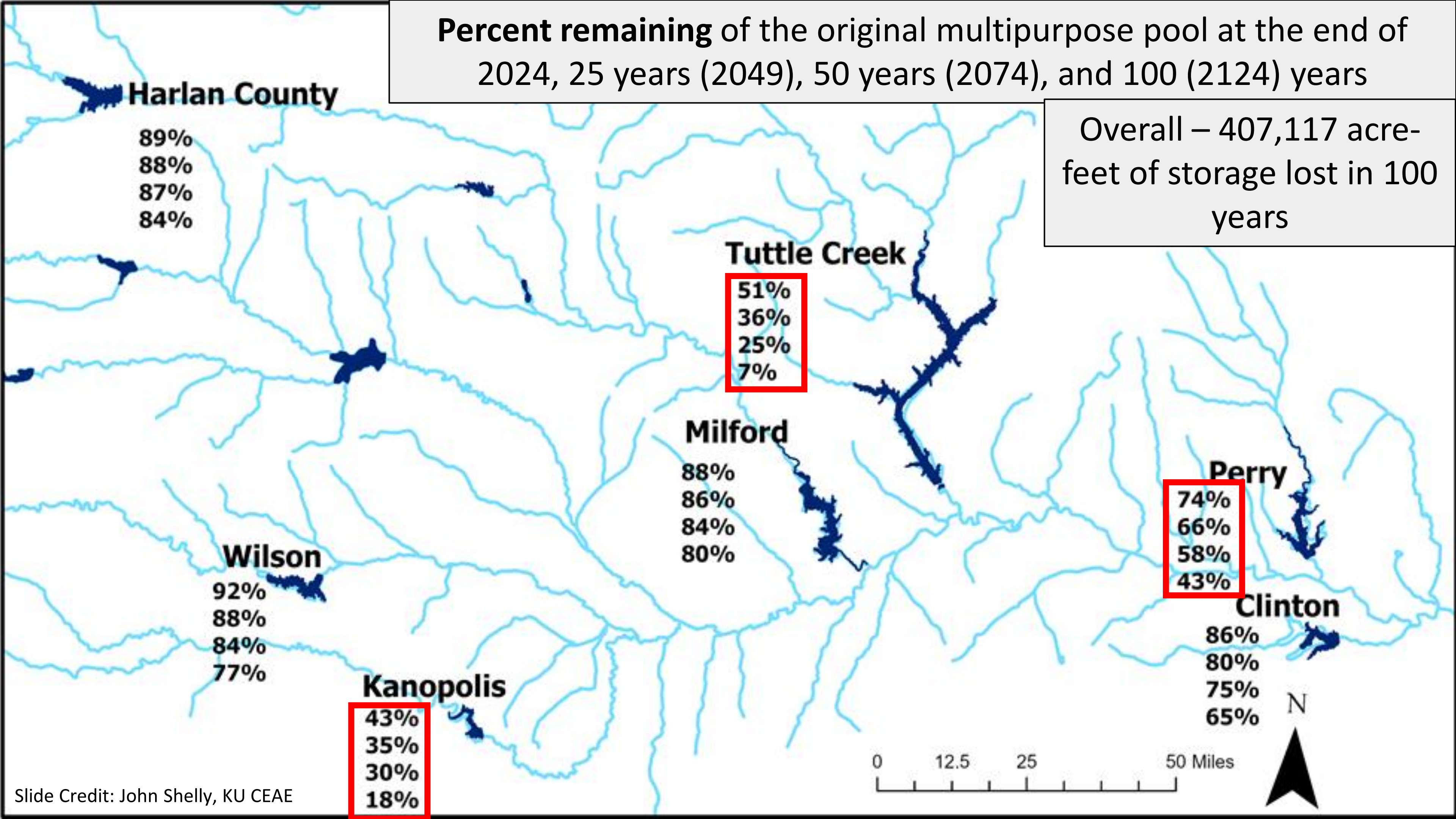
Tuttle Creek Lake



Slide Credit: John Shelly, KU CEAE

Percent remaining of the original multipurpose pool at the end of 2024, 25 years (2049), 50 years (2074), and 100 (2124) years

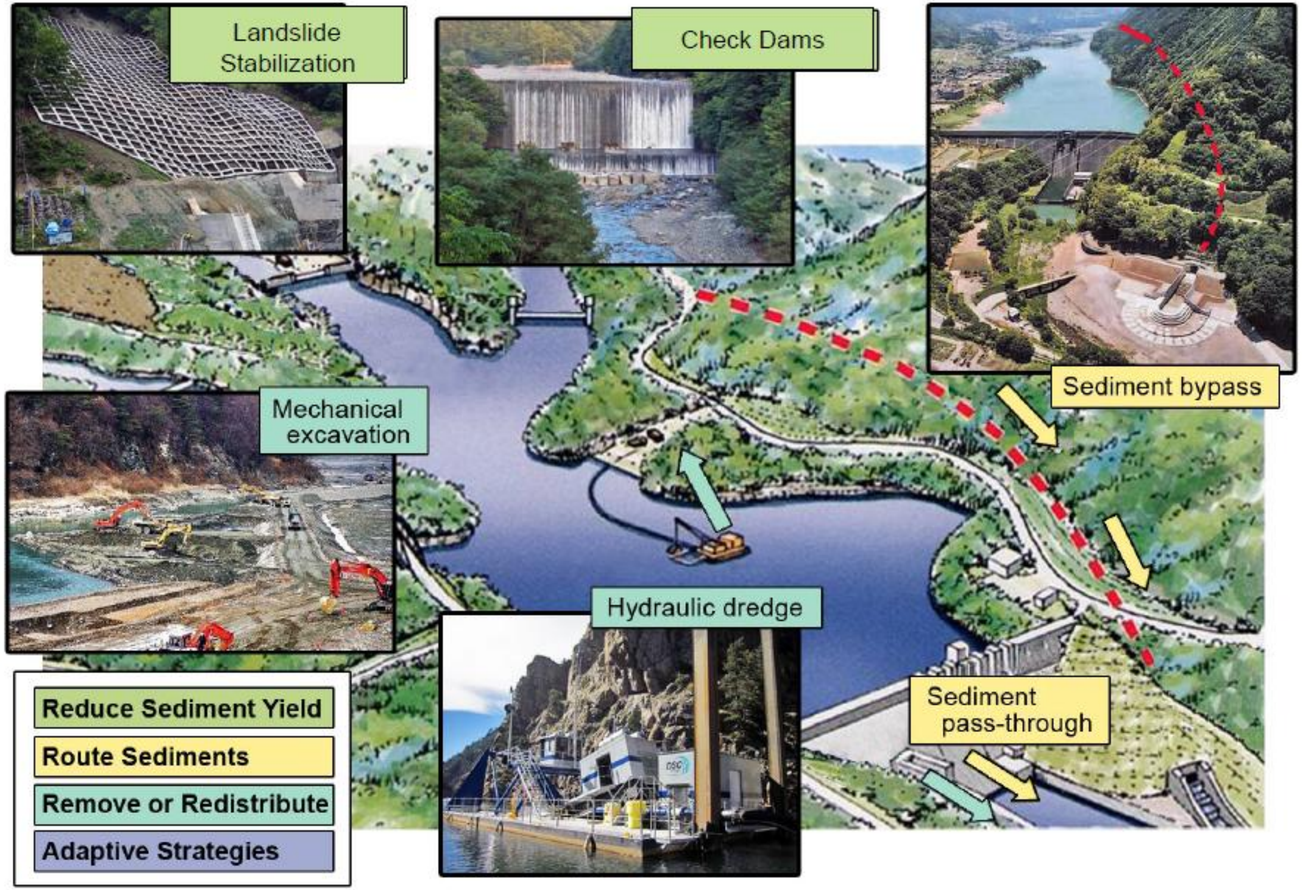
Overall – 407,117 acre-feet of storage lost in 100 years



Slide Credit: John Shelly, KU CEAE

3 basic strategies:

- Reduce
- Remove
- Route



Slide Credit: John Shelly, KU CEAE

Remove: Traditional Dredging, John Redmond, 2016

- 3 M yd^3 removed
- $20M
- $6.67/CY (2016) → ~$11/CY (2025)

John Redmond Lake, KS

Applying $11/CY to Tuttle Creek Lake…

How much would it cost just to remove **the annual deposition** from Tuttle Creek Lake using traditional dredging methods at $11/CY?

$67M+++ per year

Slide Credit: John Shelly, KU CEAE

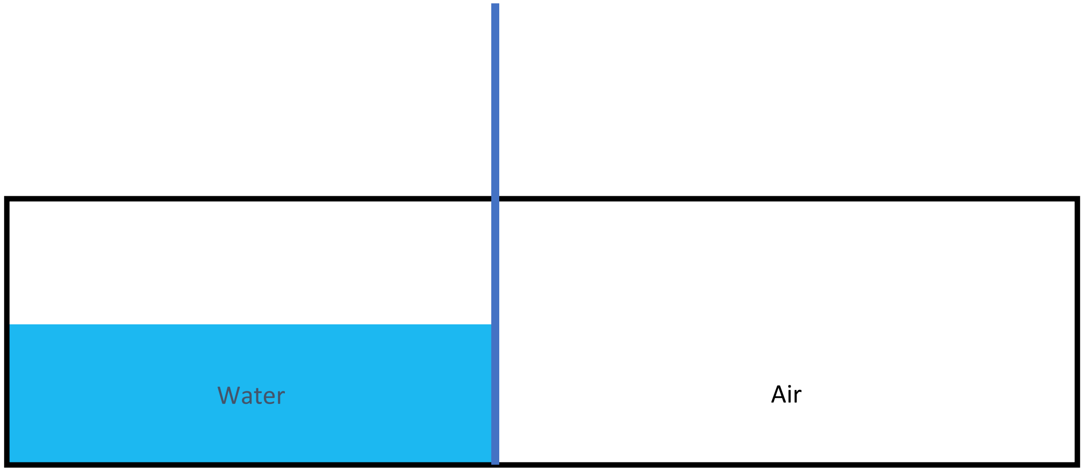
Cut the cost by 50% or more by passing the sediment downstream

Millsite Lake, UT

Slide Credit: John Shelly, KU CEAE

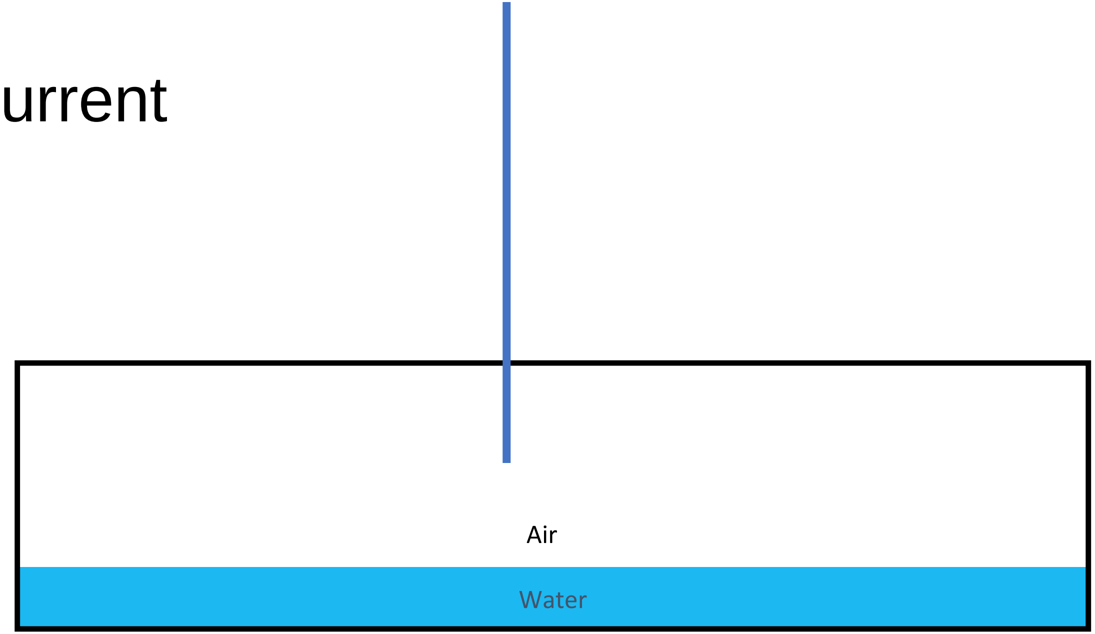
Water Injection Dredging

Density current



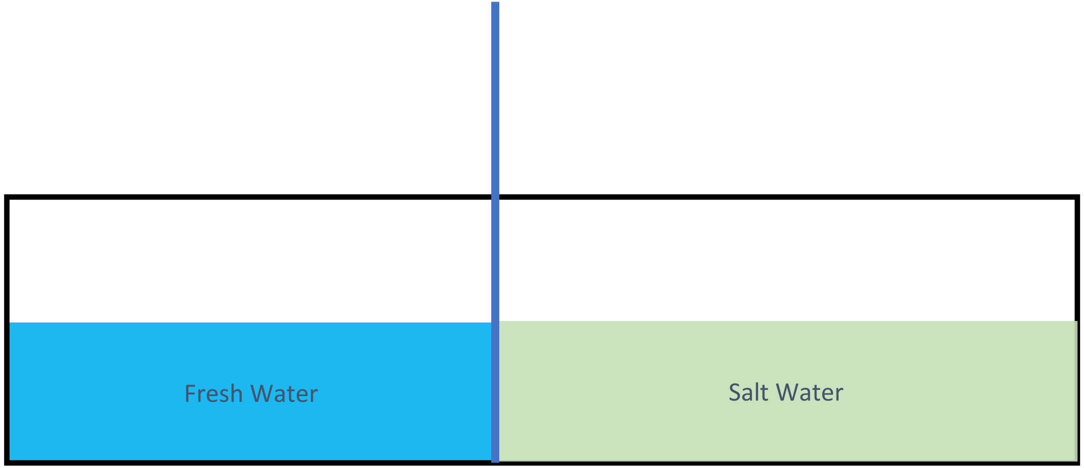
Slide Credit: Michael Mansfield, USACE

Density current



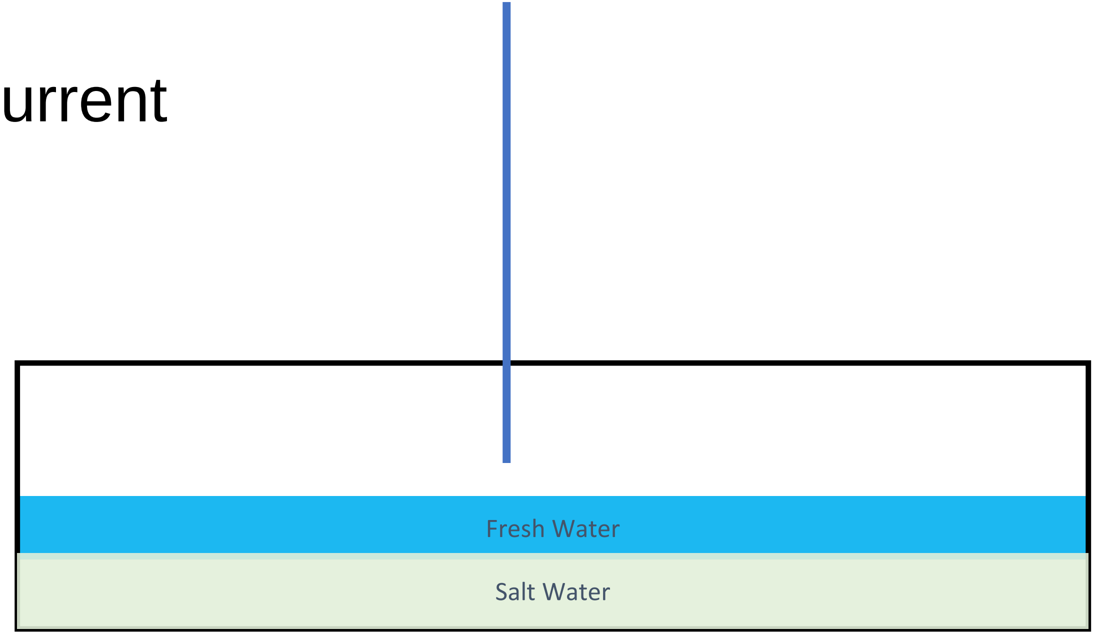
Slide Credit: Michael Mansfield, USACE

Density current



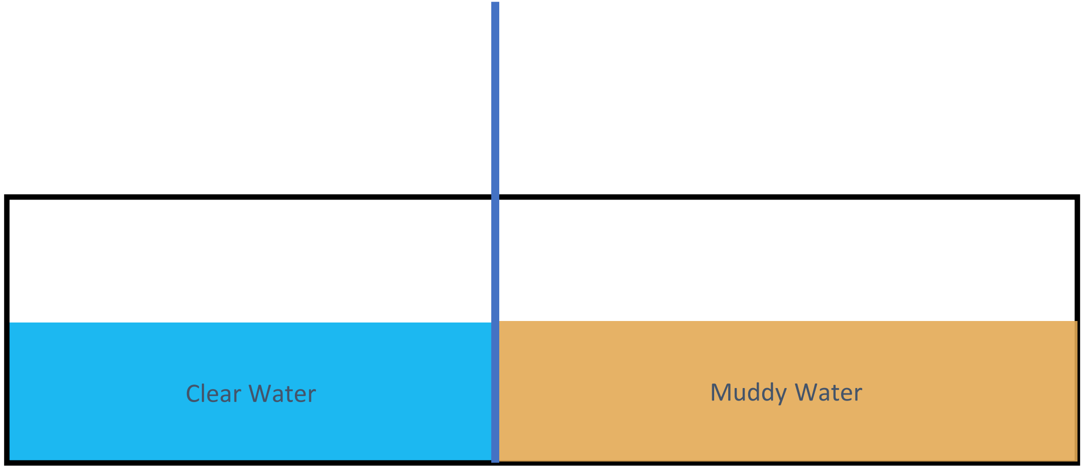
Slide Credit: Michael Mansfield, USACE

Density current



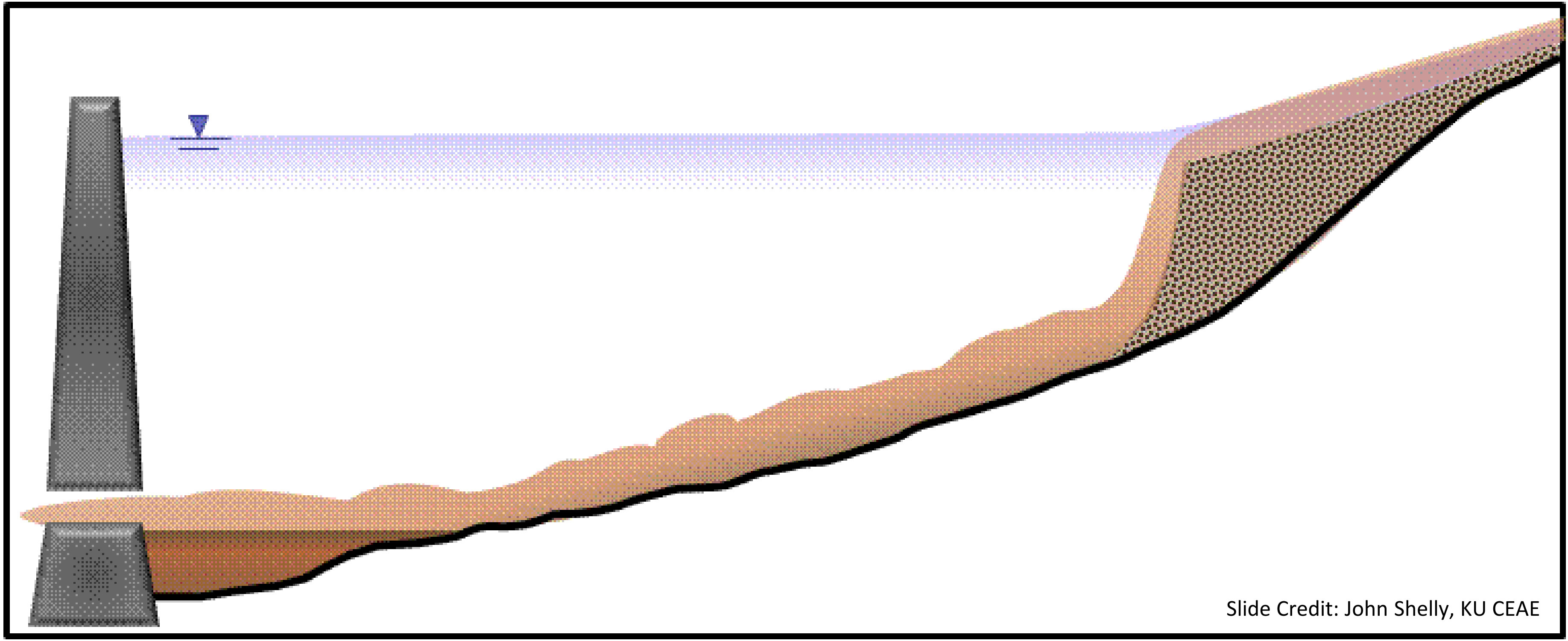
Slide Credit: Michael Mansfield, USACE

Density current



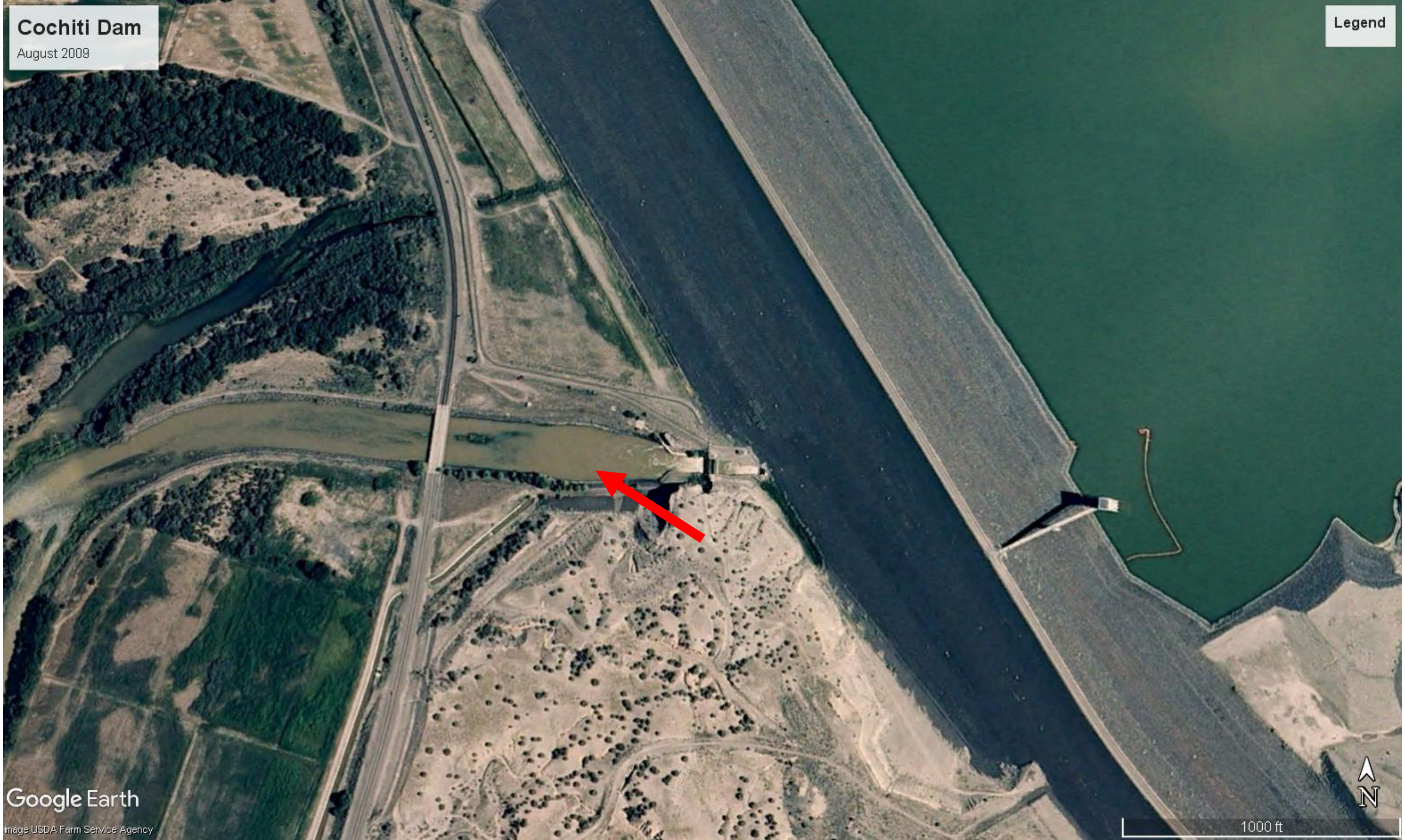
Slide Credit: Michael Mansfield, USACE

Density Currents in Lakes



Slide Credit: John Shelly, KU CEAE


Cochiti Lake
August 2009
Legend
Cochiti Lake
Google Earth
Image USDA Farm Service Agency
2 mi
N


Cochiti Dam
August 2009
Legend
Google Earth
Image USDA Farm Service Agency
1000 ft
N

Water Injection Dredging

- Induce a density current by fluidizing the top layer of sediment using water jets

- Let it flow downslope to be released through low gates

Slide Credit: John Shelly, KU CEAE

https://www.youtube.com/watch?v=J2Zikq6Zx68

Slide Credit: John Shelly, KU CEAE

Tuttle Creek Lake Water Injection Dredging Demonstration Project

- $9.1M ($7.1M Federal, $2M State of Kansas)
- First in the world application of WID in a lake

Slide Credit: John Shelly, KU CEAE

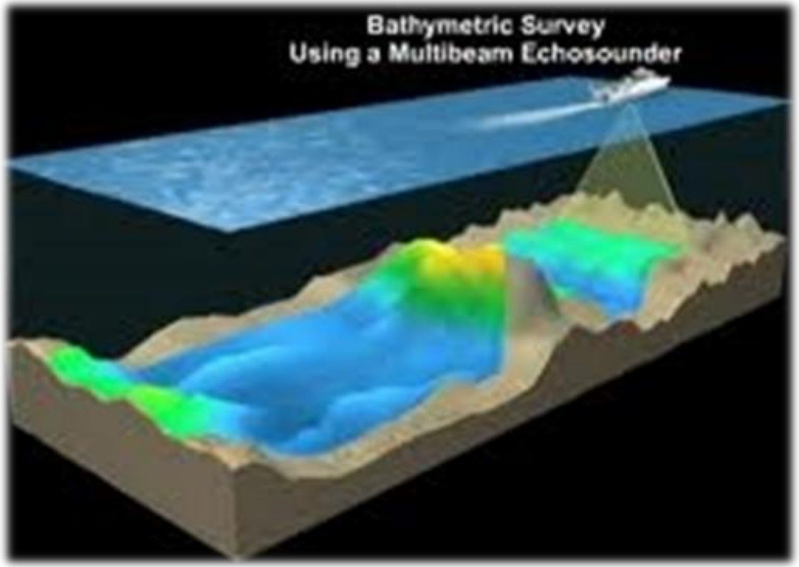
TUTTLE CREEK RESERVOIR
WATER INJECTION DREDGING DEMONSTRATION

Test of the technology– not a typical dredging project

- Goal: Answer questions
- Not: Dredge to a certain elevation or volume

Tuttle Creek Lake Primary Questions

- How much sediment can WID move?
- WID production rate (CY/hr)
- How much will it cost per cubic yard?
- What are the downstream effects? (WQ/ecological/geomorphology)
- Fully successful if we answer these questions.



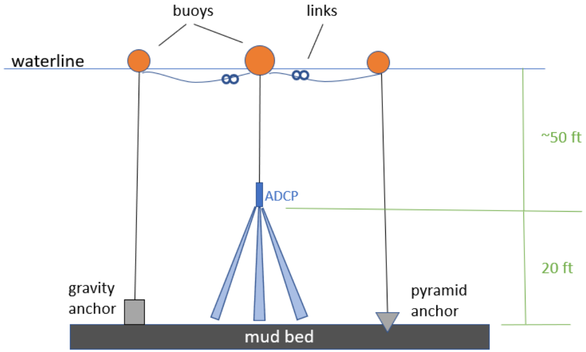
Extensive multibeam
Extensive downstream channel sediment concentrations

Slide Credit: John Shelly, KU CEAE

SECONDARY QUESTIONS

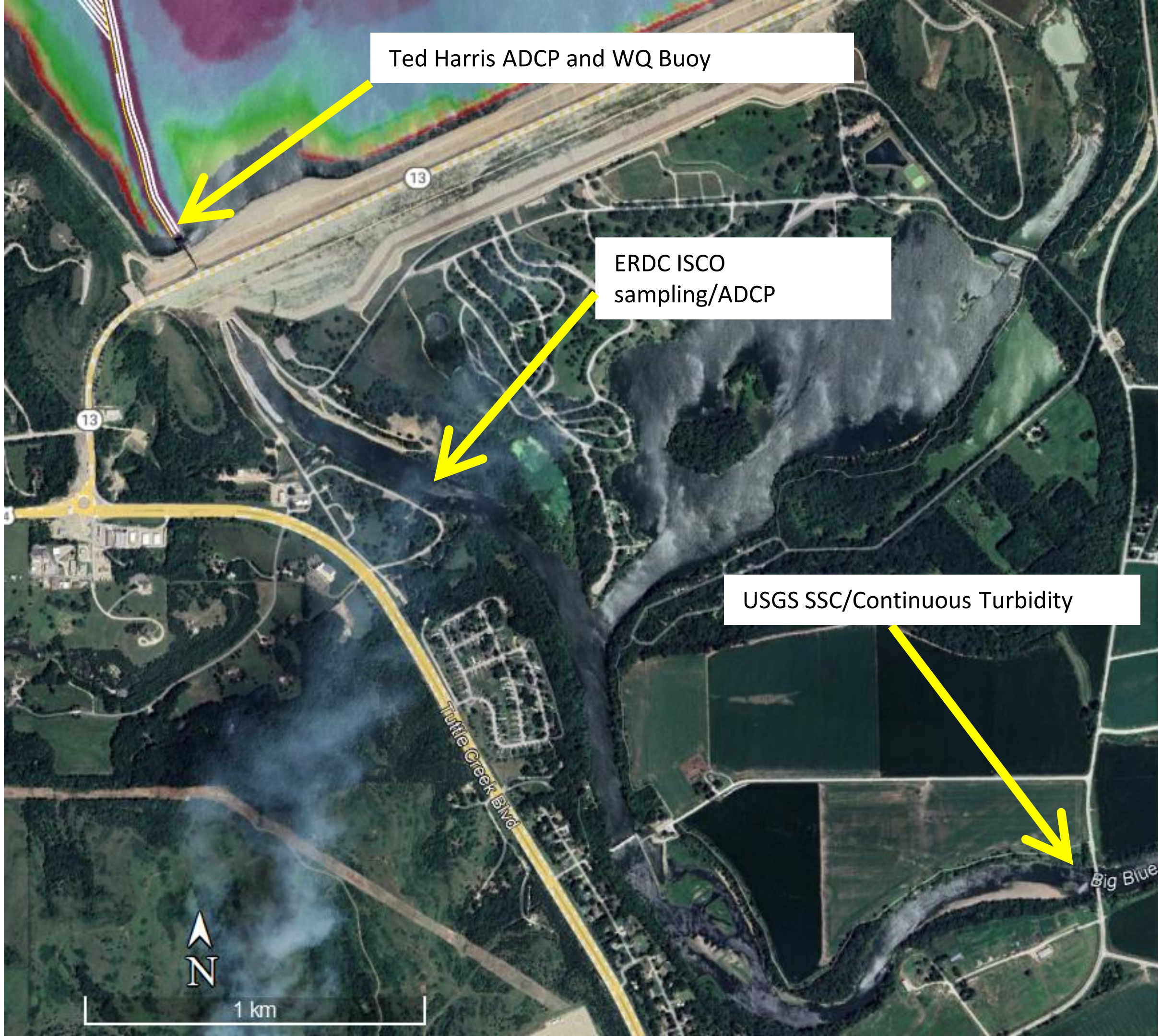
12 Different Labs/Research Centers Involved in Data Collection and Testing

- Engineer Research and Development Center (multiple sections and labs)
- University of Kansas (multiple departments and centers)
- Kansas State University (multiple departments and centers)
- Kansas Water Office
- Bureau of Reclamation
- Virginia Tech
- University of Delft, Netherlands



- How can we optimize sediment removal? (dredge speed and direction, jetbar distance to bed, number of passes, etc.)
- Factors that influence density current (sediment concentration, height, width, speed)? How do they spread laterally?
- Can numerical or empirical models be used to simulate production?
- How quickly does the sediment settle/consolidate following dredging?
- Does in-lake chemistry change?
- Downstream channel fish population response?
- Downstream channel sandbar deposition?

Slide Credit: John Shelly, KU CEAE



Ted Harris ADCP and WQ Buoy

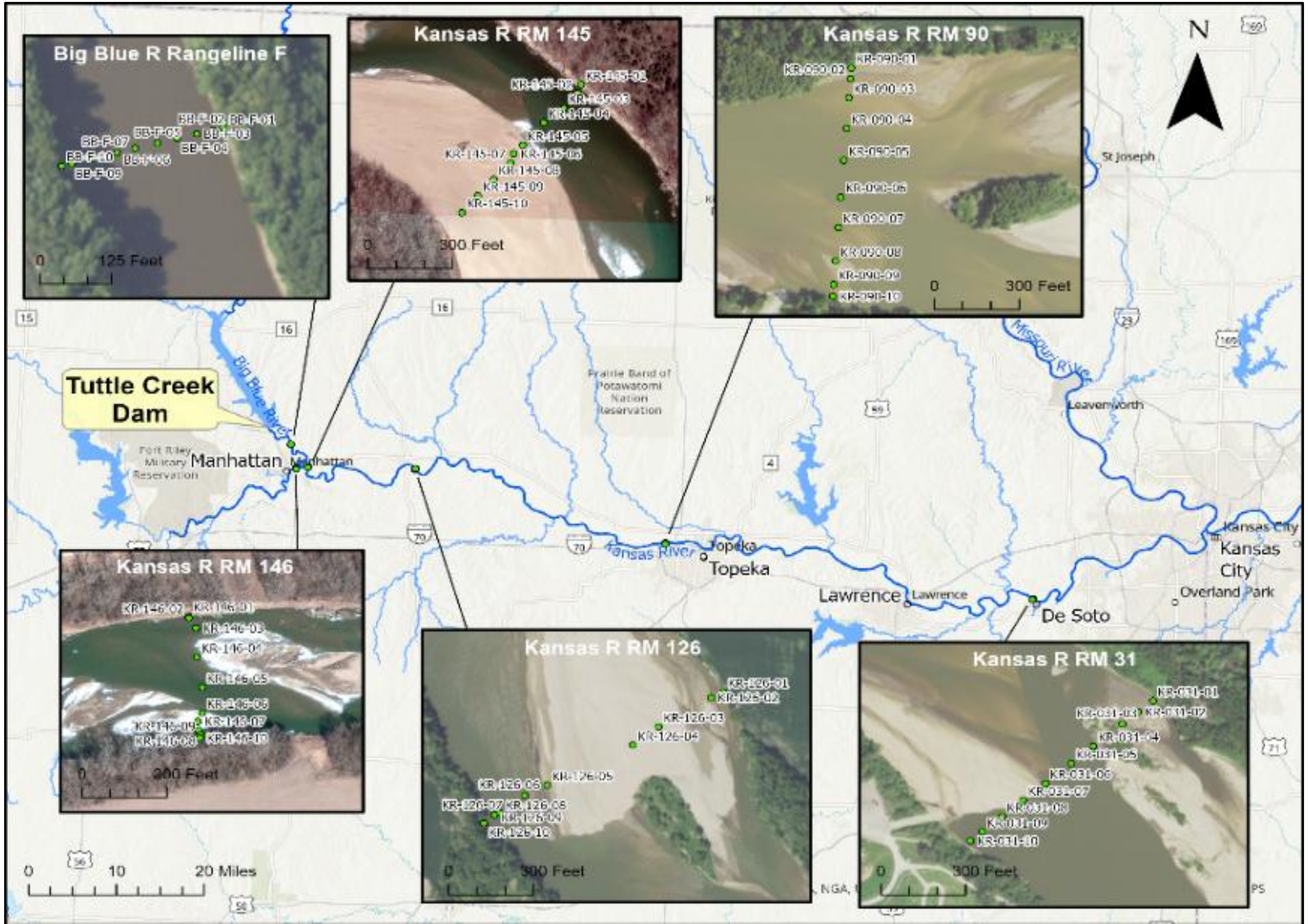
ERDC ISCO
sampling/ADCP

USGS SSC/Continuous Turbidity

Slide Credit: John Shelly, KU

Downstream Channel Monitoring Program

- 5 continuous gage stations (turbidity/water quality)
- Additional pre/post water/sediment quality measurements
- Cross-sections
- Bed/sandbar sediment
- Invertebrates

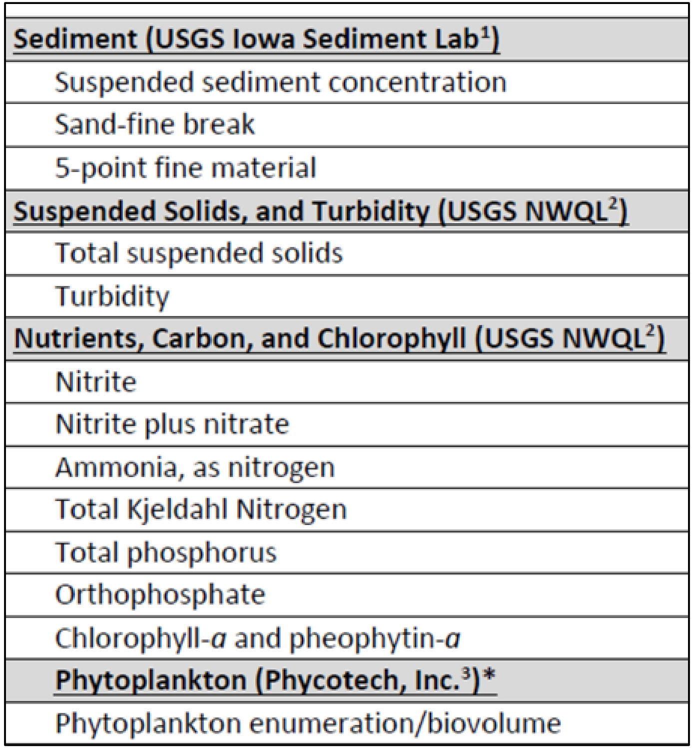


Slide Credit: John Shelly, KU CEAE

WATER/SEDIMENT QUALITY PARAMETERS

- **Physical measures collected with multi-parameter physical water quality instrument:** Water Temperature (C°), pH (S.U), Dissolved Oxygen (mg/L), Conductivity (umhos/cm), Turbidity (NTU).

- **Chemical Laboratory Analysis (ERDC):** Ammonia as N, Total (mg/L), Total Kjeldahl Nitrogen (mg/L), Nitrate / Nitrite as N (mg/L), Phosphorus – Total (mg/L), Phosphorus – Soluble Reactive (orthophosphorus) (mg/L), Suspended Sediment Concentration (mg/L), Total Suspended Solids (mg/L), Total Hardness (CaCO3 mg/L),Total Organic Carbon (mg/L), Dissolved Organic Carbon (mg/L), Chloride (mg/L), Bromide (mg/L), Sulfate (mg/L), Total Metals (mg/L) (Mercury, Cadmium, Copper, Chromium, Lead, Nickel, Zinc) Total Atrazine (ug/L), Taste and Odor Compounds in drinking water –Geosmin (ug/L), 2-Methylisoborneol (MIB) (ug/L), Phytoplankton ID/Count (cells/ml), Total microcystin (ug/L), Chlorophyll a (ug/L), Pheophytin (ug/L), Biological Oxygen Demand (mg/L).



Sediment (USGS Iowa Sediment Lab[1])
Suspended sediment concentration
Sand-fine break
5-point fine material
Suspended Solids, and Turbidity (USGS NWQL[2])
Total suspended solids
Turbidity
Nutrients, Carbon, and Chlorophyll (USGS NWQL[2])
Nitrite
Nitrite plus nitrate
Ammonia, as nitrogen
Total Kjeldahl Nitrogen
Total phosphorus
Orthophosphate
Chlorophyll-*a* and pheophytin-*a*
Phytoplankton (Phycotech, Inc.[3])*
Phytoplankton enumeration/biovolume

Slide Credit: John Shelly, KU CEAE