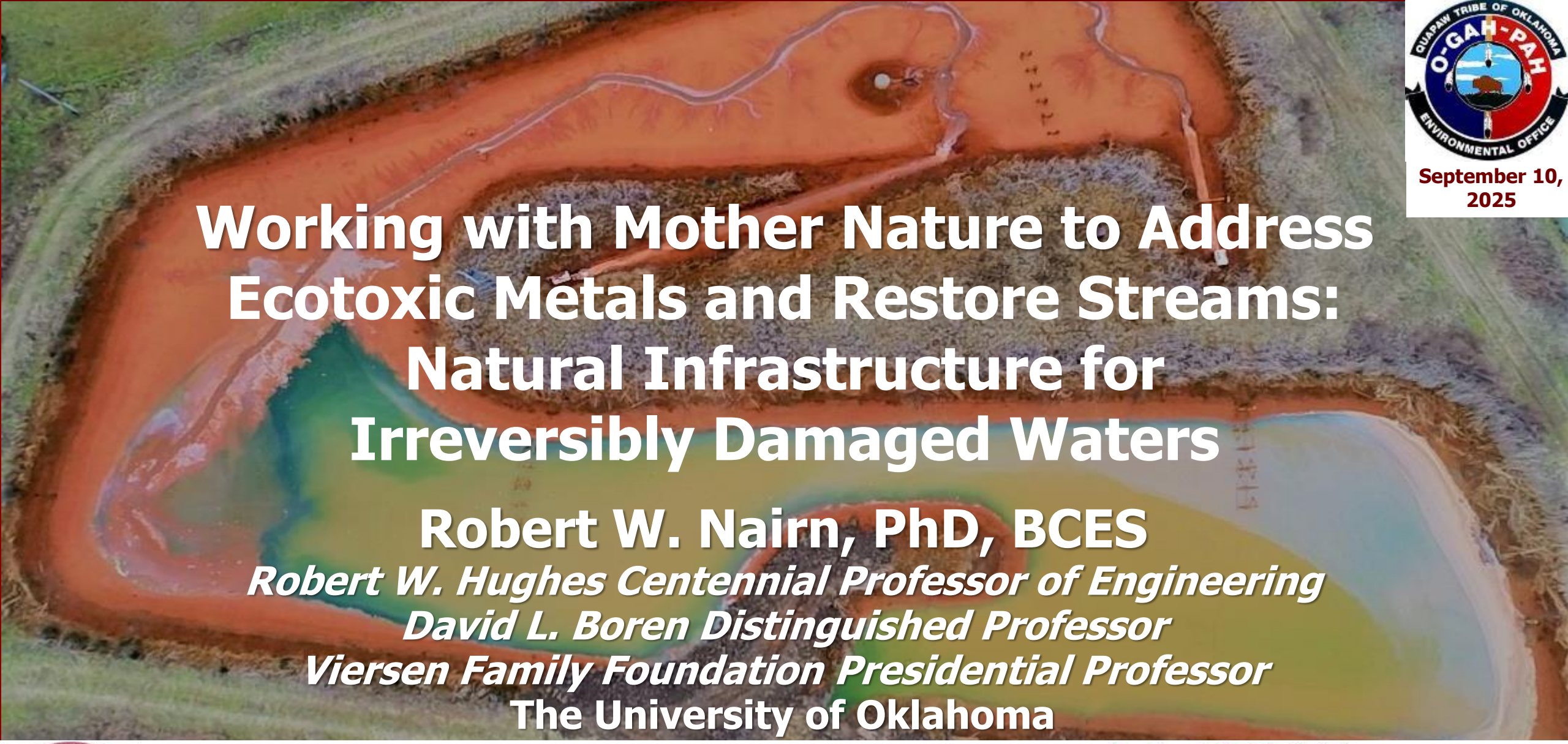


September 10, 2025

Working with Mother Nature to Address Ecotoxic Metals and Restore Streams: Natural Infrastructure for Irreversibly Damaged Waters

Robert W. Nairn, PhD, BCES

Robert W. Hughes Centennial Professor of Engineering

David L. Boren Distinguished Professor

Viersen Family Foundation Presidential Professor

The University of Oklahoma

GALLOGLY COLLEGE OF ENGINEERING
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE
The UNIVERSITY of OKLAHOMA

CREW
Center for Restoration of Ecosystems and Watersheds
The University of Oklahoma

The land on which the University of Oklahoma resides was the traditional home of the “Hasinais” Caddo Nation and “Kirikir?i:s” Wichita and Affiliated Tribes and served as a hunting ground, trade exchange point, and migration route for the Apache, Comanche, Kiowa and Osage Nations.

Today, 39 Nations dwell in the state of Oklahoma as a result of settler and colonial policies.

The University recognizes the historical connection our university has with its Indigenous community. We acknowledge, honor and respect the diverse Indigenous peoples connected to this land. We fully recognize, support and advocate for the sovereign rights of all of Oklahoma’s 39 Tribal Nations.

Beaver pond wetlands
The Nature Conservancy's Boehler Seeps and Sandhills Preserve
Atoka County, OK

Traditional Infrastructure

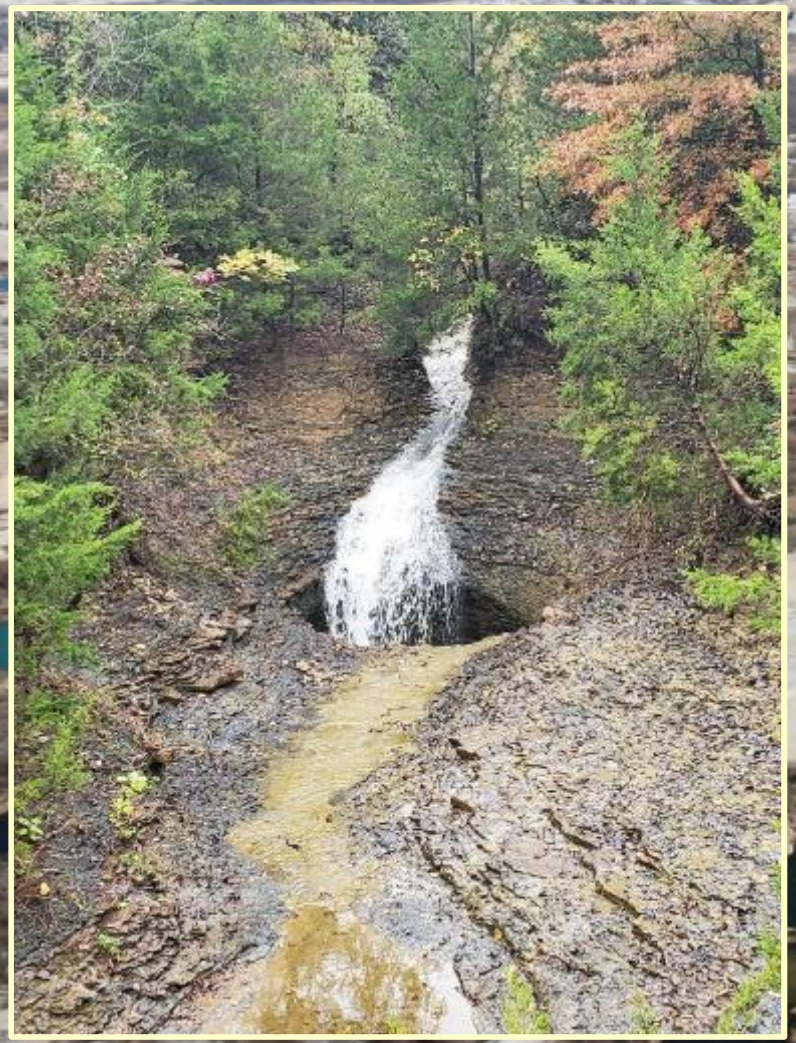
City of Norman Water Reclamation Facility, Norman, OK

Natural Infrastructure

East Fork Water Reuse Project and John Bunker Sands Wetlands Center, Combine, TX

Can we apply these ideas to a drastically disturbed watershed like Tar Creek?

Tar Creek Watershed, Ottawa County, OK – A landscape in need of natural infrastructure!

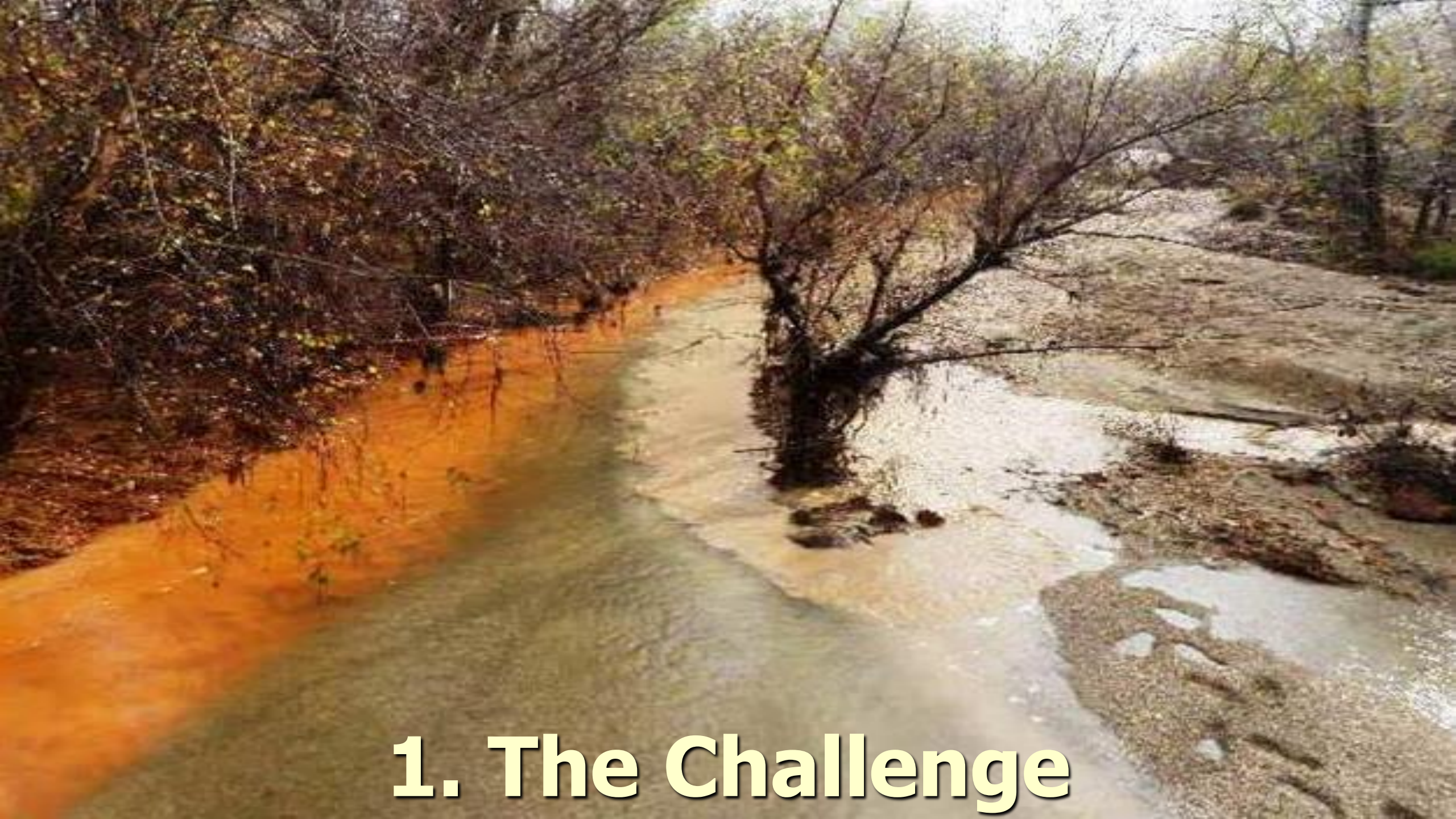



1. The Challenge


2. Natural Infrastructure


3. Receiving Stream Recovery

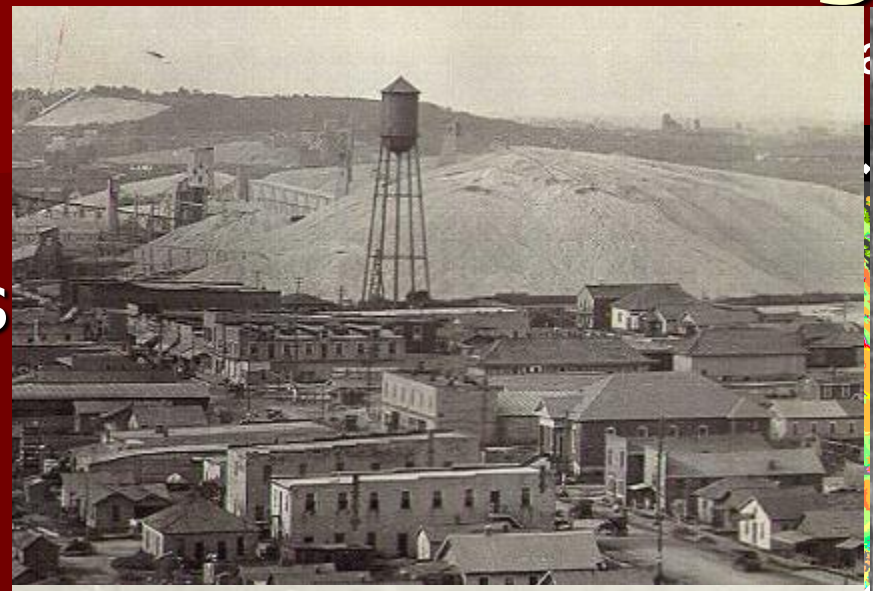

4. Conclusions

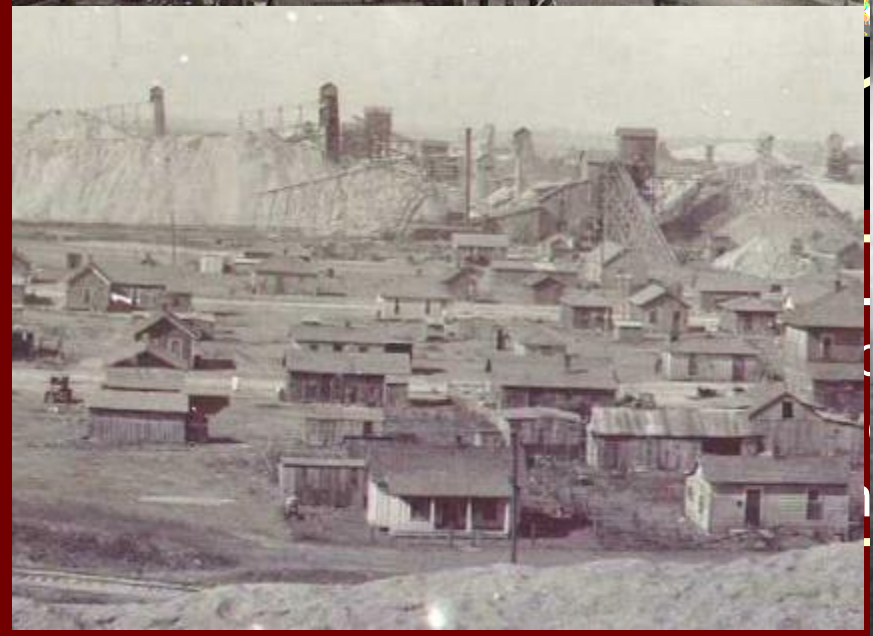


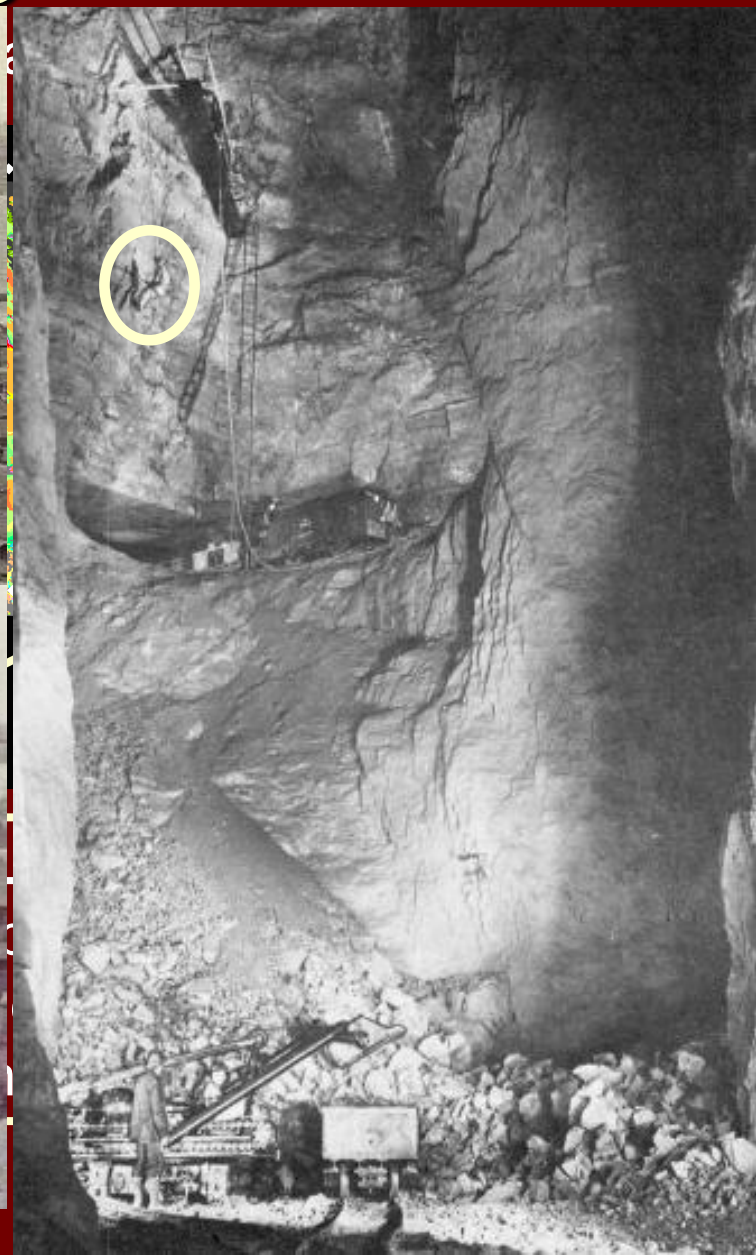
1. The Challenge

Tri-State Lead-Zinc Mining District

- >3000 km^2 mined ≈1838-1971
- Mississippian sulfides
  - Galena (PbS)
  - Sphalerite (ZnS)
- Extensive underground workings
- Massive surface processing operations







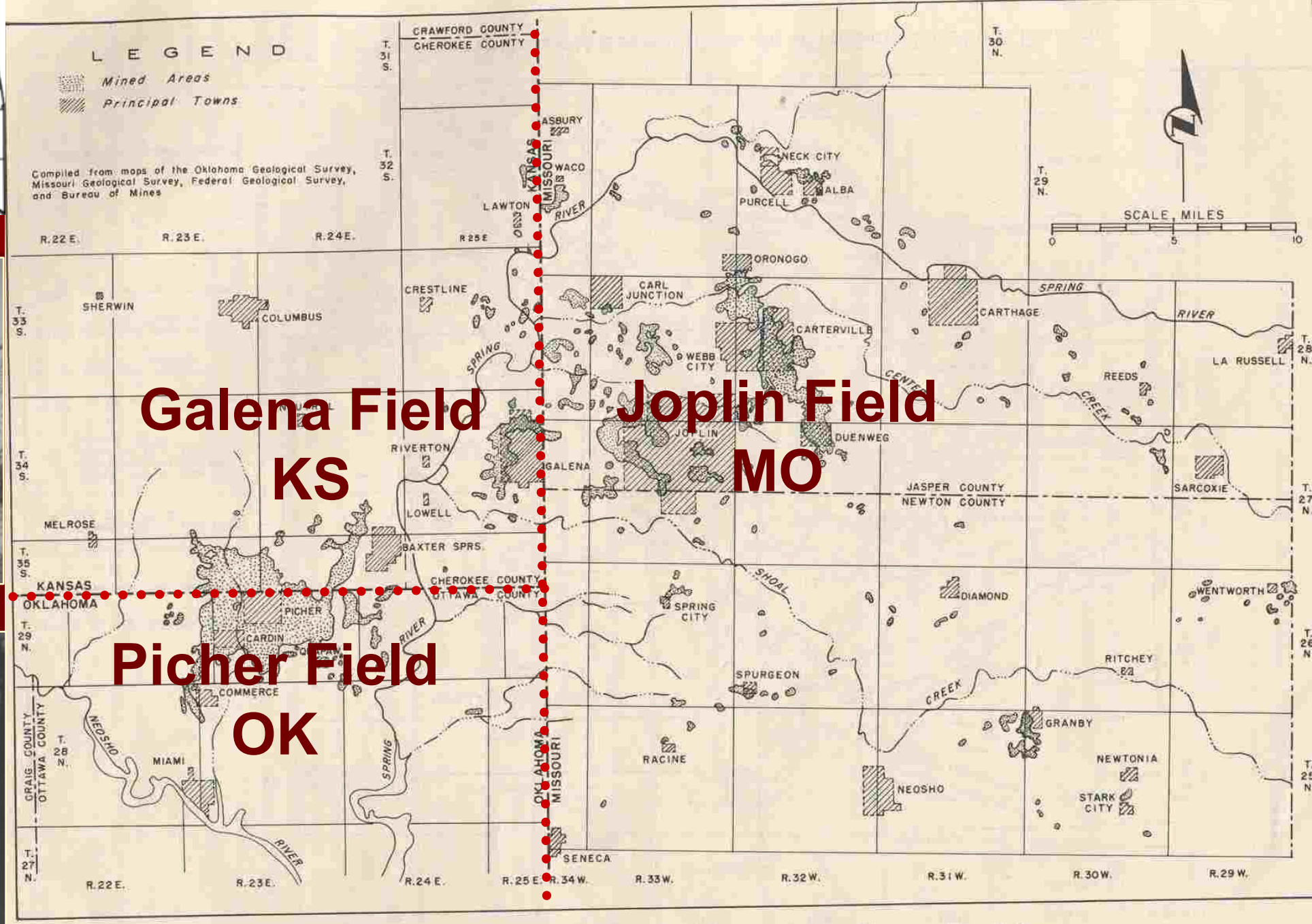


FIGURE 1. - Principal Part of Tri-State Zinc-Lead District, Showing Mined Areas.

Cherokee County Superfund Site

Tar Creek (Ottawa County) Superfund Site

Oronogo-Duenweg Mining Belt Superfund Site

Newton County Mine Tailings Superfund Site

FIGURE 1. - Principal Part of Tri-State Zinc-Lead District, Showing Mined Areas.

Mining-Related Water Quality Concerns

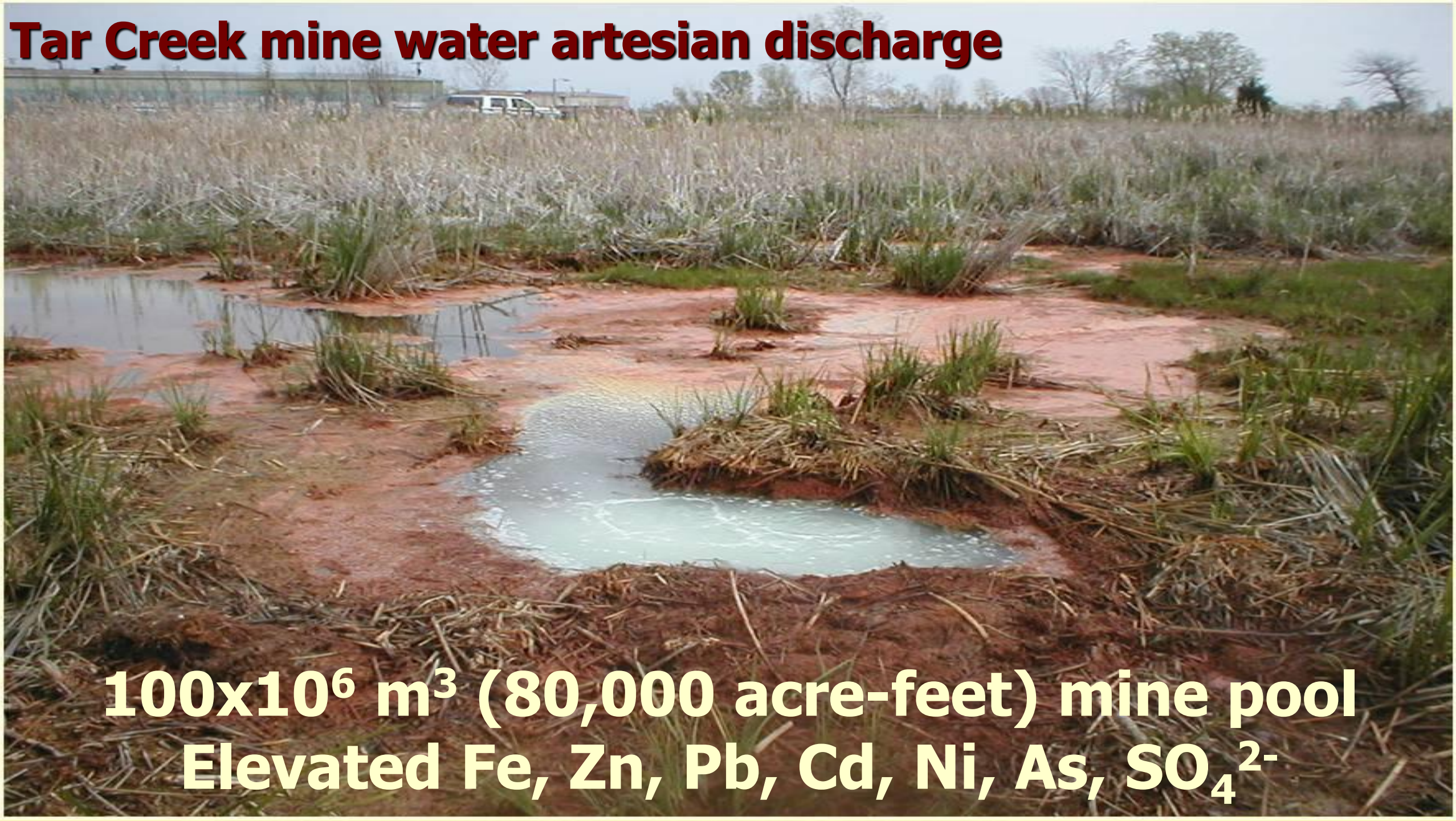
Sulfide minerals + O_2 + H_2O + bacteria

↓

Acidity + Metals + Sulfate

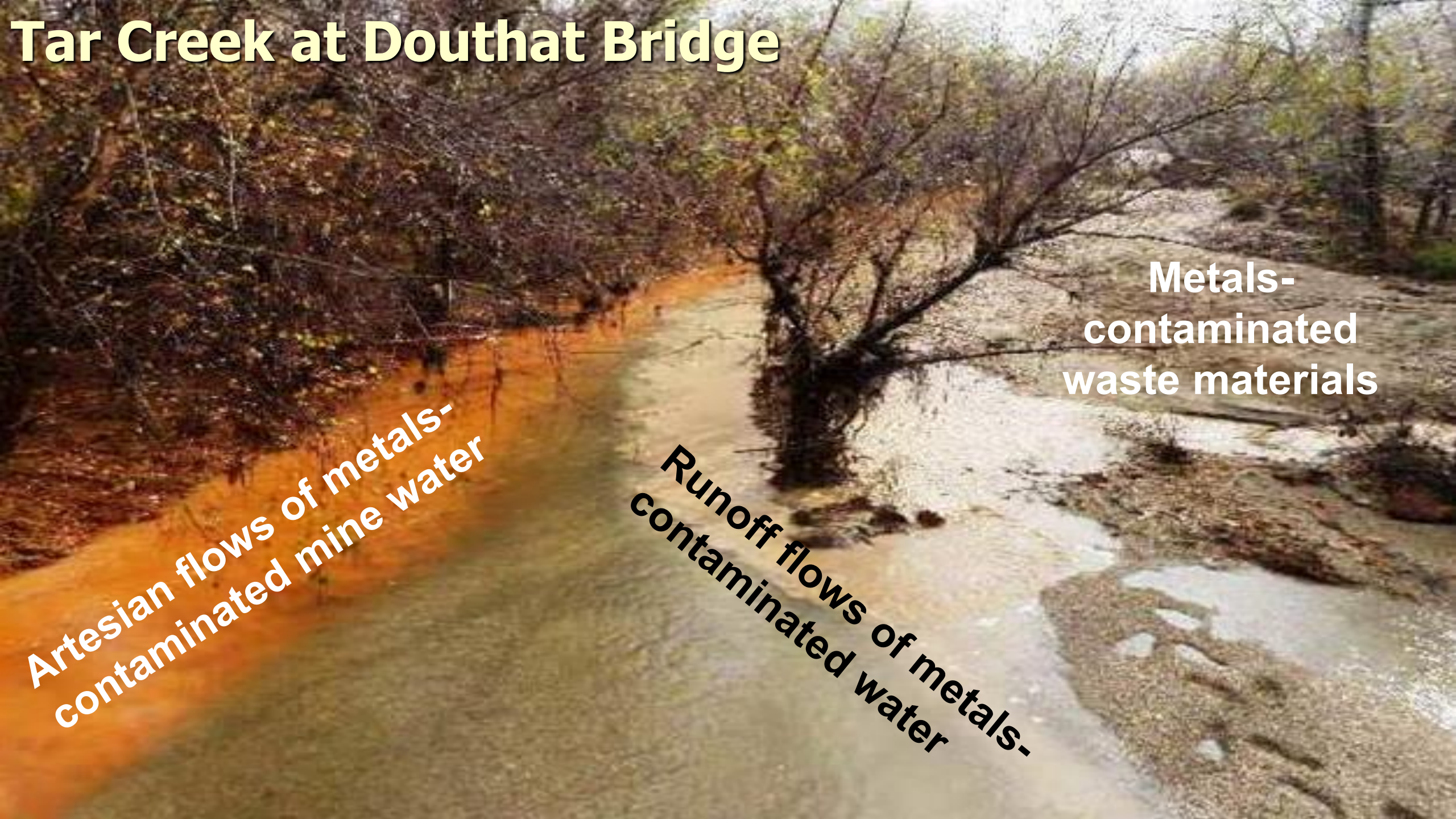
- ↑ Mineral, $H_2CO_3^*$, proton acidity
- ↑ Trace Metals: Fe, Zn, Pb, Cd, As, Ni, Mn, Al, Cu, Co, and others
- ↑ SO_4^{2-}, Cl^-, HCO_3^-
- ↑ Ca, Mg, Na, K, and others

Tar Creek mine water artesian discharge



100×10^6 m^3 (80,000 acre-feet) mine pool

Elevated Fe, Zn, Pb, Cd, Ni, As, SO_4^{2-}


Tar Creek at Douthat Bridge
Metals-contaminated waste materials
Artesian flows of metals-contaminated mine water
Runoff flows of metals-contaminated water

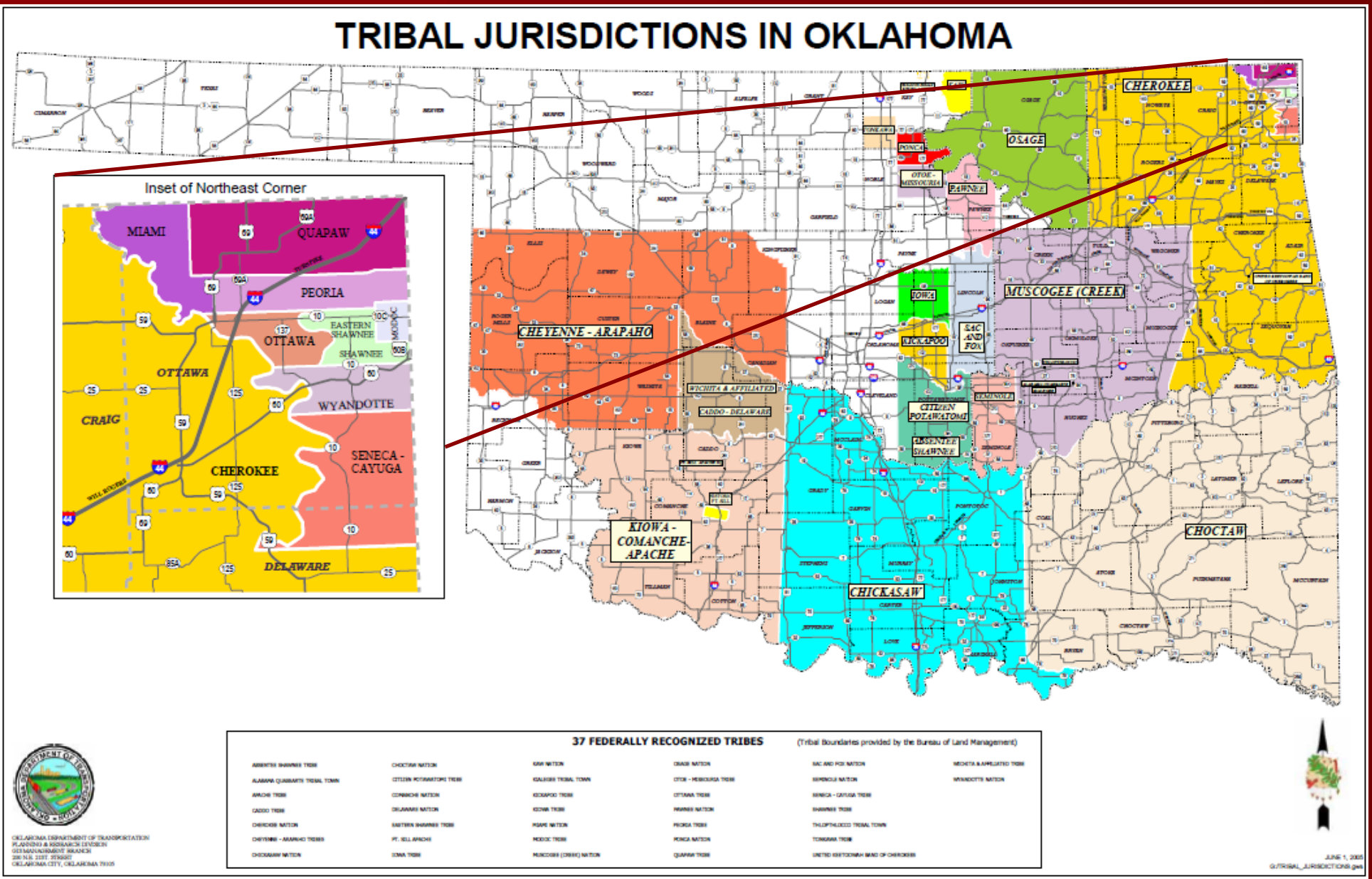
Ottawa County

- Household income ≈ 60% US median
- Poverty rate 1.7 x US median
- 37% underrepresented groups

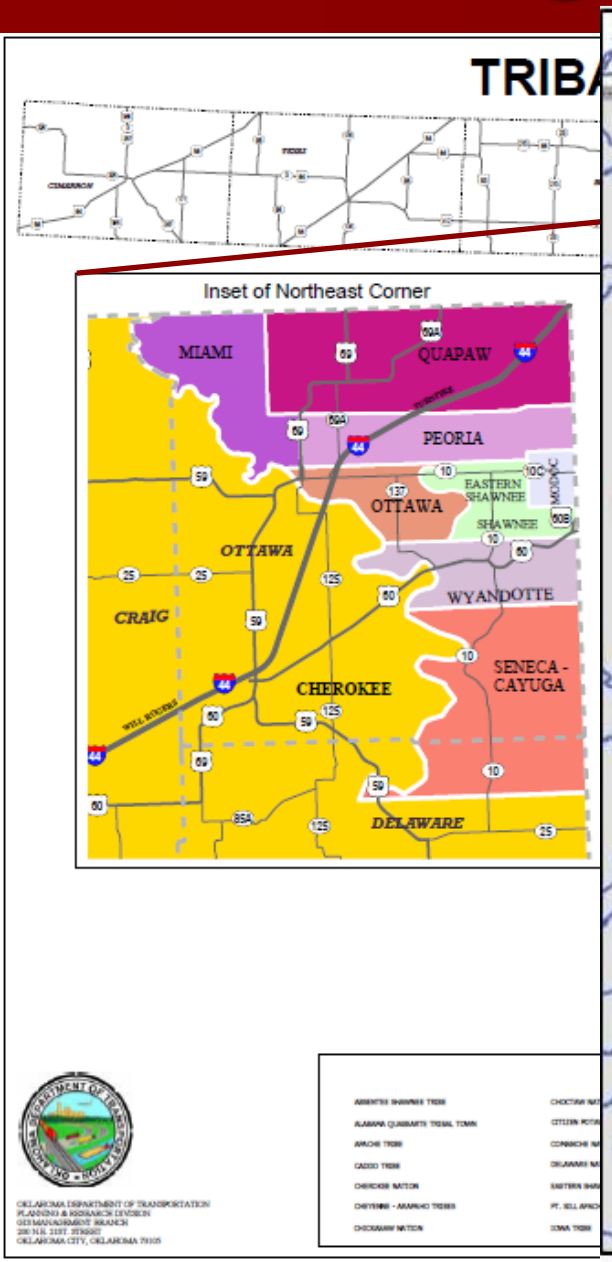
Some mining communities

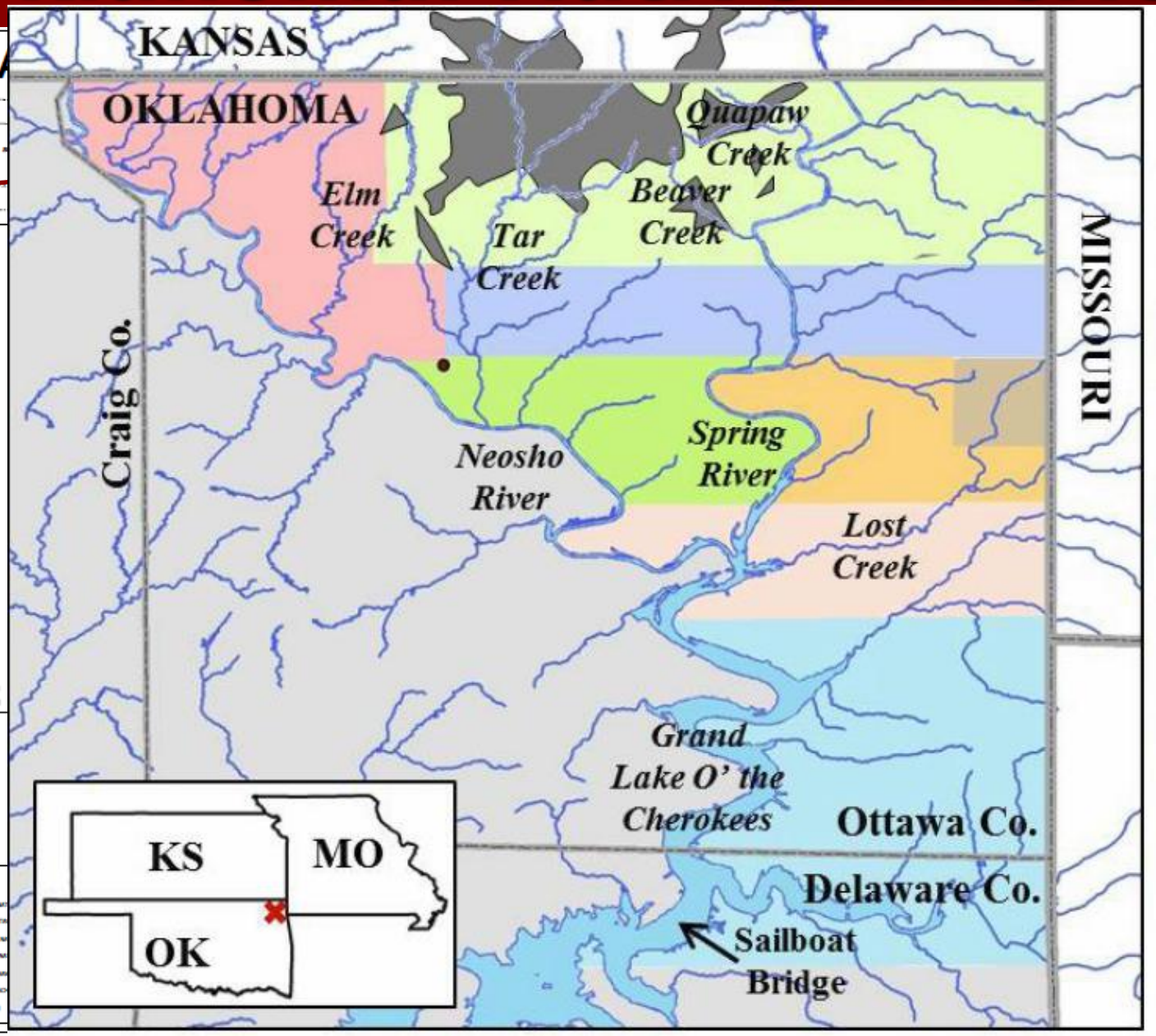
- 2009 targeted buy-out and relocation

Oklahoma: *Native America*



Oklahoma: *Native America*





Irreversible Damage?

1979: Initial metal-contaminated artesian discharges begin flowing
1983: Final listing on Superfund National Priorities List
1984: Operable Unit 1 Surface and Ground Water Record of Decision (USEPA OU1 ROD)

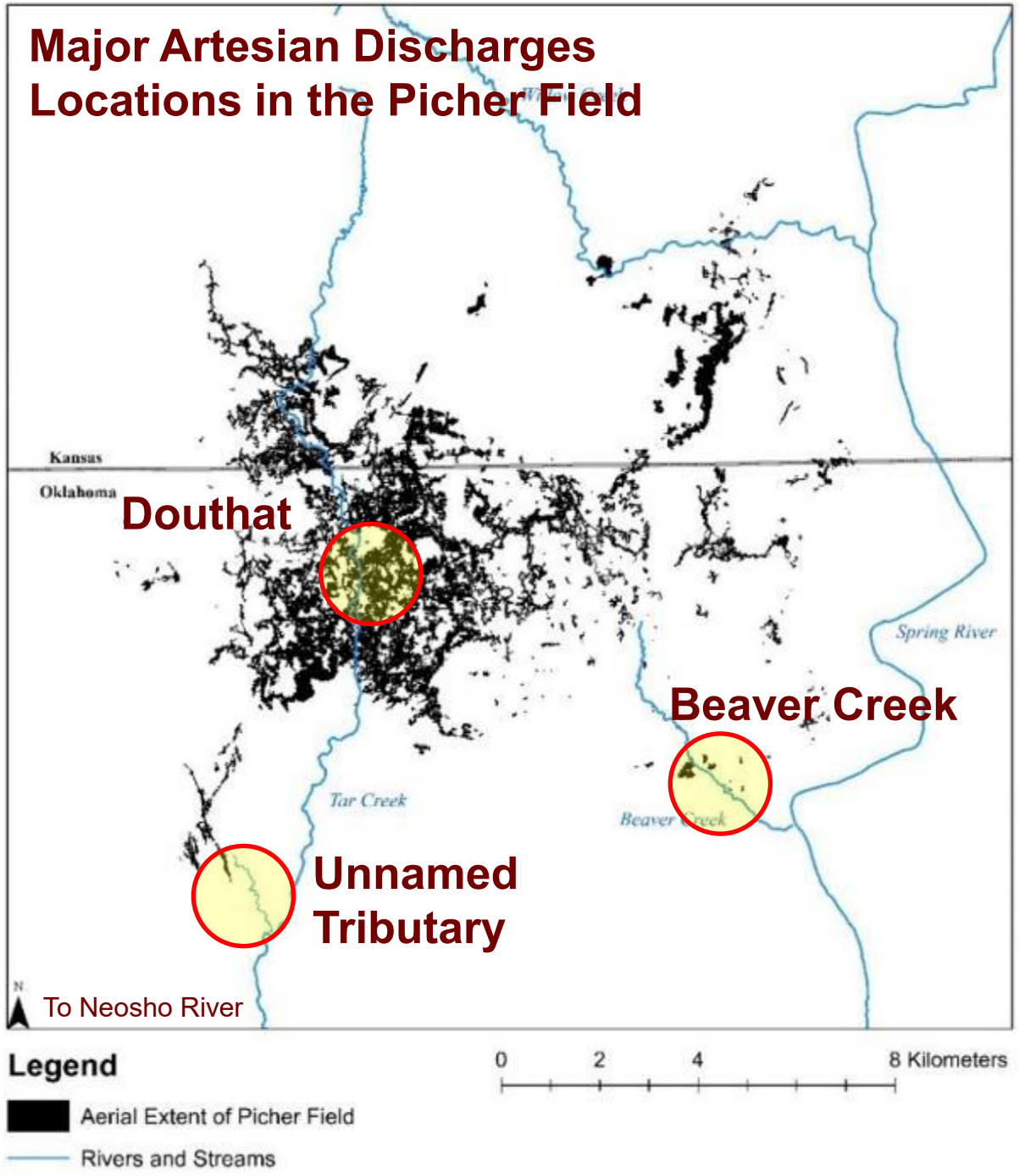
- Re-designation of beneficial use classification:

  "impacts to (surface waters) are due to ***irreversible man-made damages*** *resulting from past mining operations at the site"*

- Fund-balancing waiver notes costs prohibitively high to address surface water contamination

CREW
Center for Restoration of Ecosystems and Watersheds
The University of Oklahoma

- CREW research efforts (1997-)
  - Mine pool, surface water, groundwater
  - Artesian discharges, streams, runoff, leachate
  - Soils, sediments, terrestrial and aquatic biota
- Major focus
  - **Passive treatment of artesian discharges**
  - **Unnamed Tributary watershed**

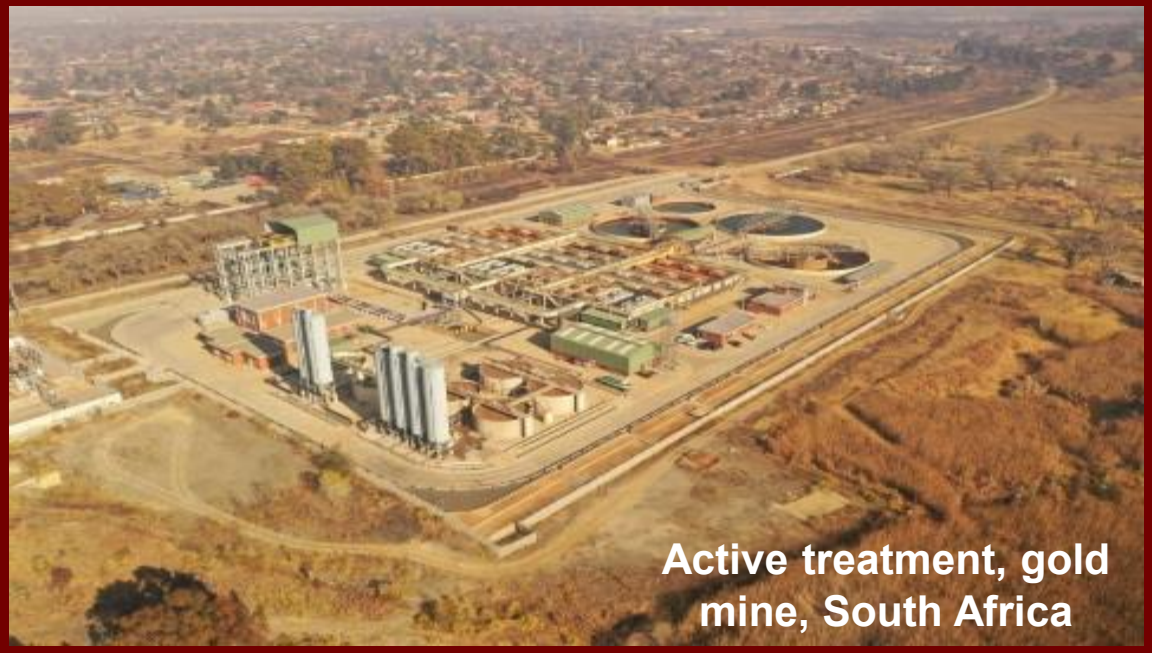



Is it true?
"impacts to (surface waters) are due to irreversible man-made damages resulting from past mining operations at the site"
After 46 years of unabated mine water flows?

Mine Water Treatment Options

Active

- Chemical additions
- Substantial external energies
- Laborious and expensive
- Significant capital expenses
- Greater operation and maintenance



Active treatment, gold mine, South Africa

Passive

- Natural biogeochemical, microbiological, and ecological processes
- Hydrologic- and solar-energy driven
- Limited capital expense
- Lower operation and maintenance

Passive treatment, abandoned lead-zinc mine, Tar Creek Superfund Site, Oklahoma

2. Natural Infrastructure

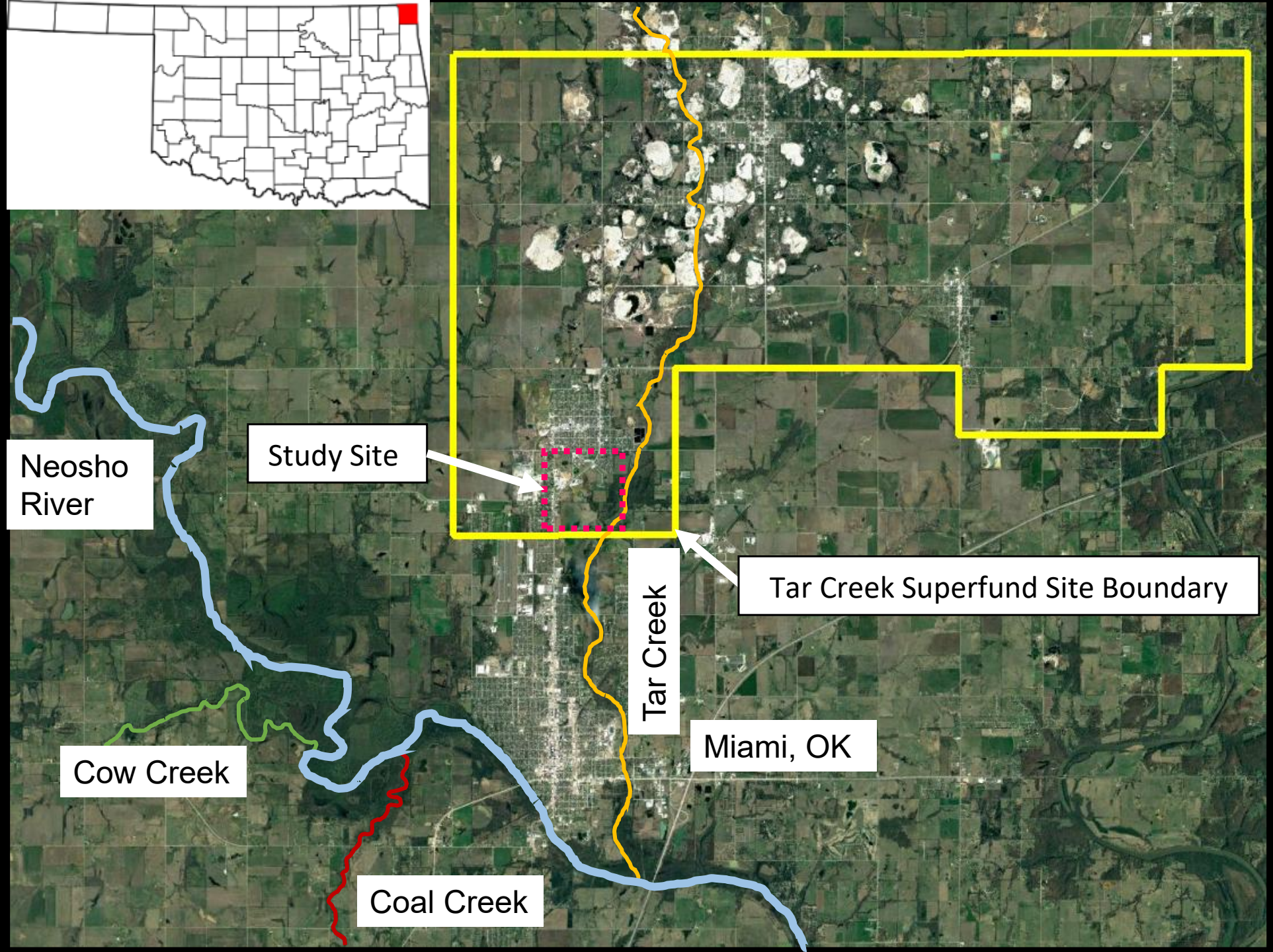
Passive Treatment Conceptual Designs

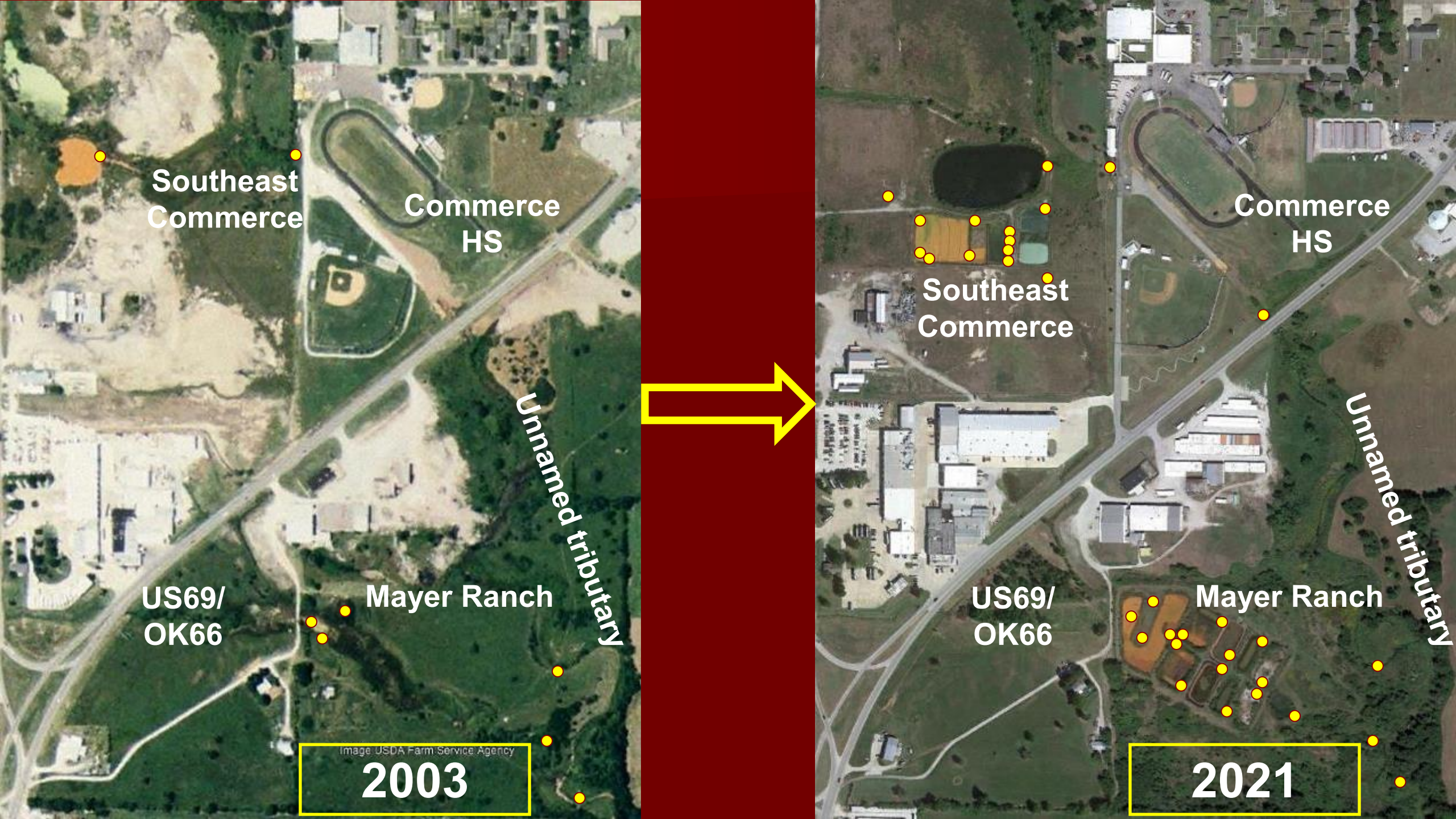
- Based on > decade of research studies
- Targeted contaminant removal
  - Oxidation reactions
  - Reduction reactions
  - Sorption
  - Precipitation
- Sequential process units



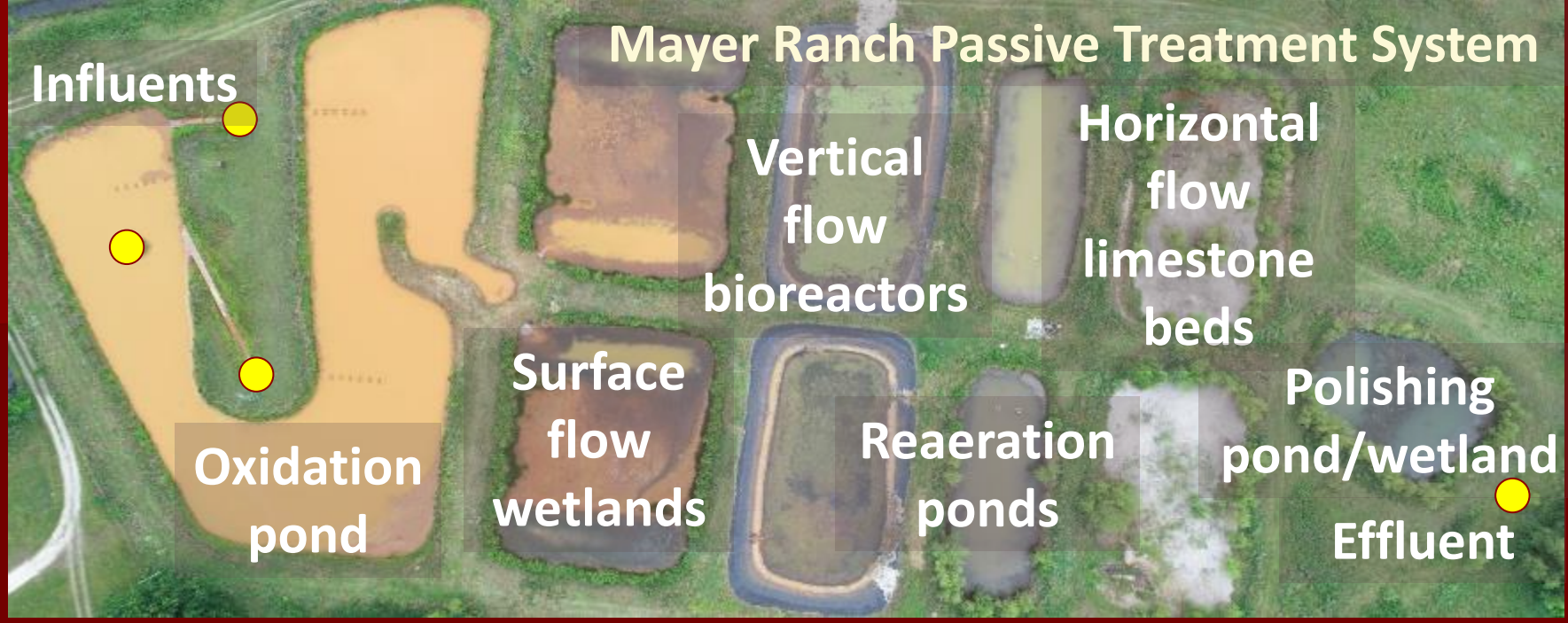





Neosho River
Study Site
Tar Creek Superfund Site Boundary
Tar Creek
Miami, OK
Cow Creek
Coal Creek


Southeast Commerce
Commerce HS
Unnamed tributary
US69/ OK66
Mayer Ranch
Image USDA Farm Service Agency
2003
Southeast Commerce
Commerce HS
Unnamed tributary
US69/ OK66
Mayer Ranch
2021

- Mayer Ranch
  - USEPA CWA 104(b)(3) funding
  - Online 11/2008
  - 10 process units
  - Flow = 420 lpm
  - Area = 2.25 ha



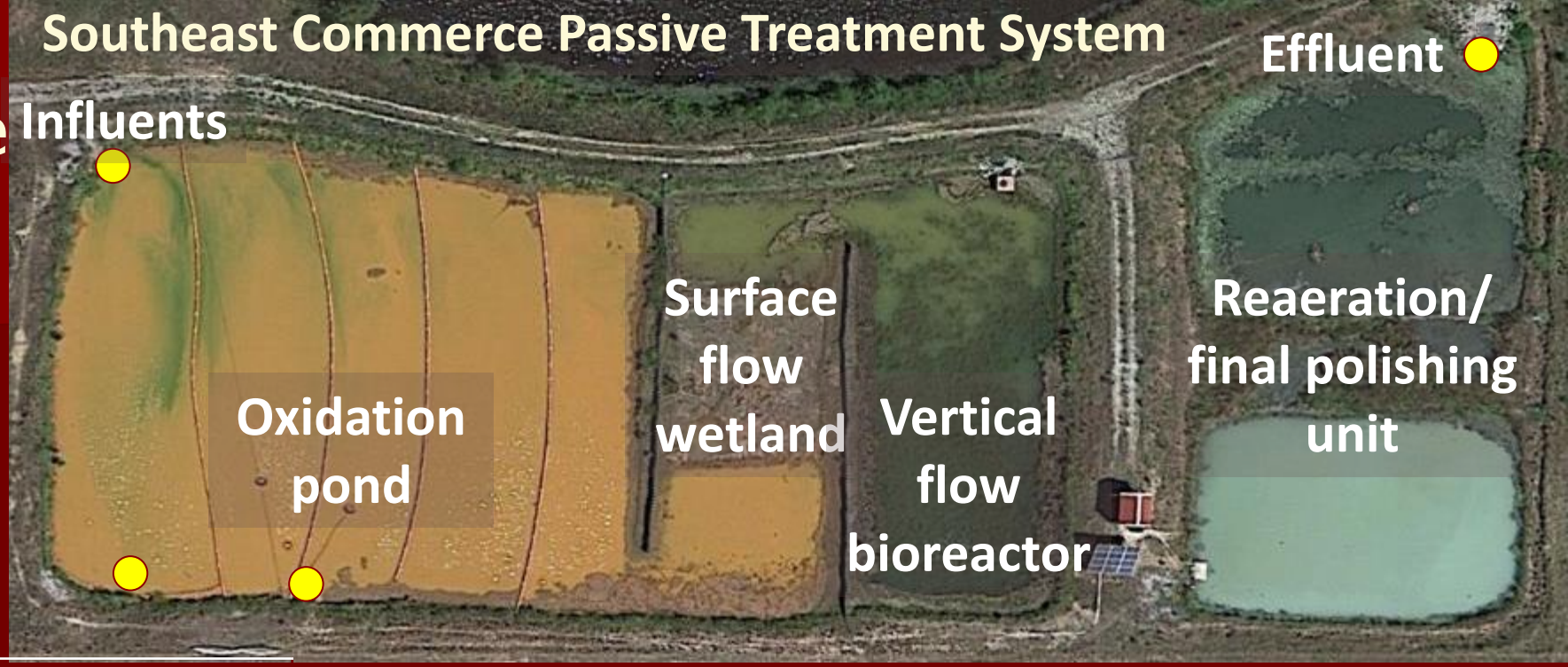
Water quality changes

	In	Out
pH	5.97	7.06
Fe (mg/L)	160	0.33
Zn (mg/L)	6.91	0.14
Pb (mg/L)	0.093	<PQL
Cd (mg/L)	0.015	<PQL

Mass retention

	Annual (kg)	16-Years (kg)
Fe	36500	584000
Zn	1550	24800
Pb	20	320
Cd	3.3	53

- Southeast Commerce
  - OSEE/DEQ funding
  - Online 02/2017
  - 4 process units
  - Flow = 600 lpm
  - Area = 1 ha



Water quality changes

	In	Out
pH	5.94	6.83
Fe (mg/L)	140	0.79
Zn (mg/L)	6.54	0.07
Pb (mg/L)	0.279	<PQL
Cd (mg/L)	0.195	<PQL

Mass retention

	Annual (kg)	8-Years (kg)
Fe	34700	277600
Zn	1575	12600
Pb	64	512
Cd	5	40

Oxidative Processes

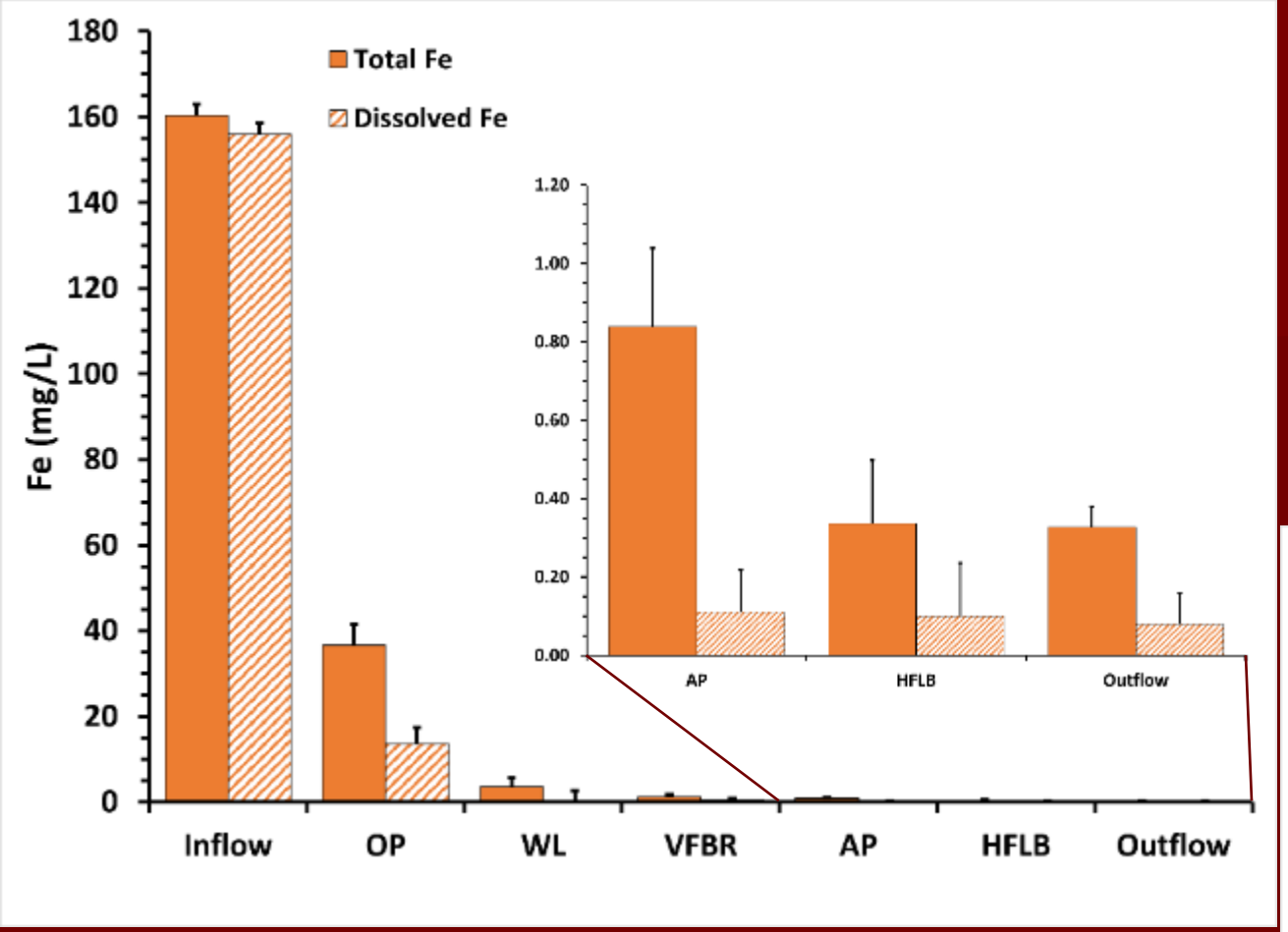
- Oxidize, hydrolyze, precipitate Fe
- Sorb As, Pb, and Cd
- Utilize off-grid aeration
- Potential resource recovery

MRPTS oxidation cell under construction, fall 2008

MRPTS oxidation cell during managed drawdown, winter 2017

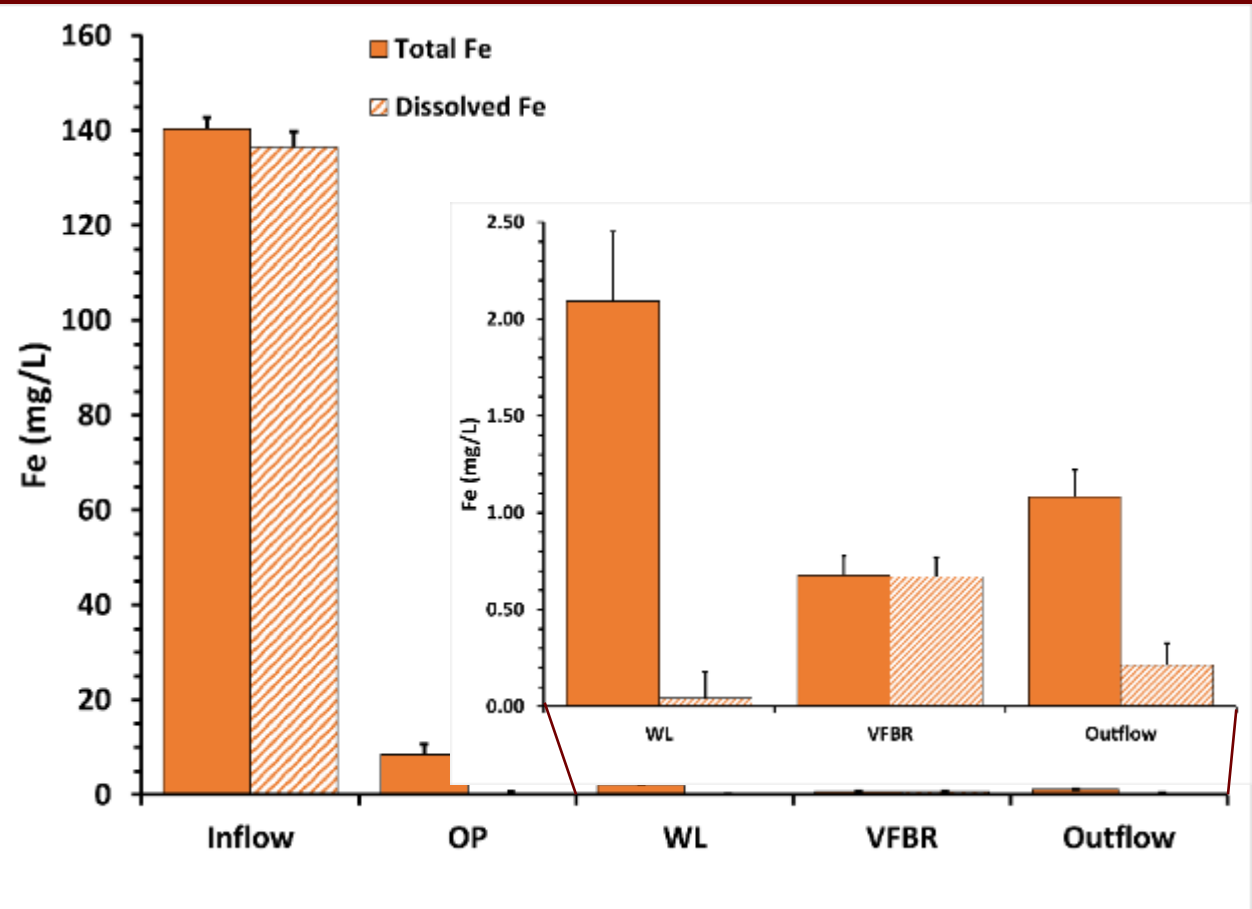
SECPTS oxidation cell directional baffle curtains, early 2017

SECPTS oxidation cell solar-powered aerators, early 2017



MRPTS Fe retention
2008-2022
(n=62)
≥ 20 g m^{-2} d^{-1} in OP

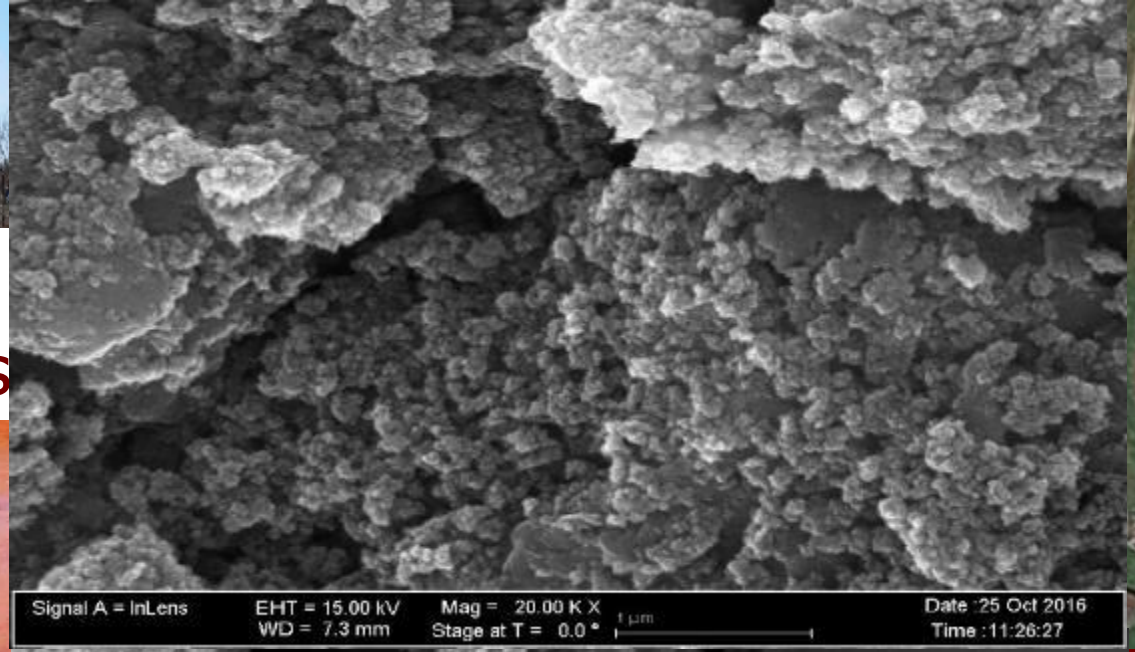
SECPTS Fe retention
2017-2022
(n=38)
≥ 20 g m^{-2} d^{-1} in OP

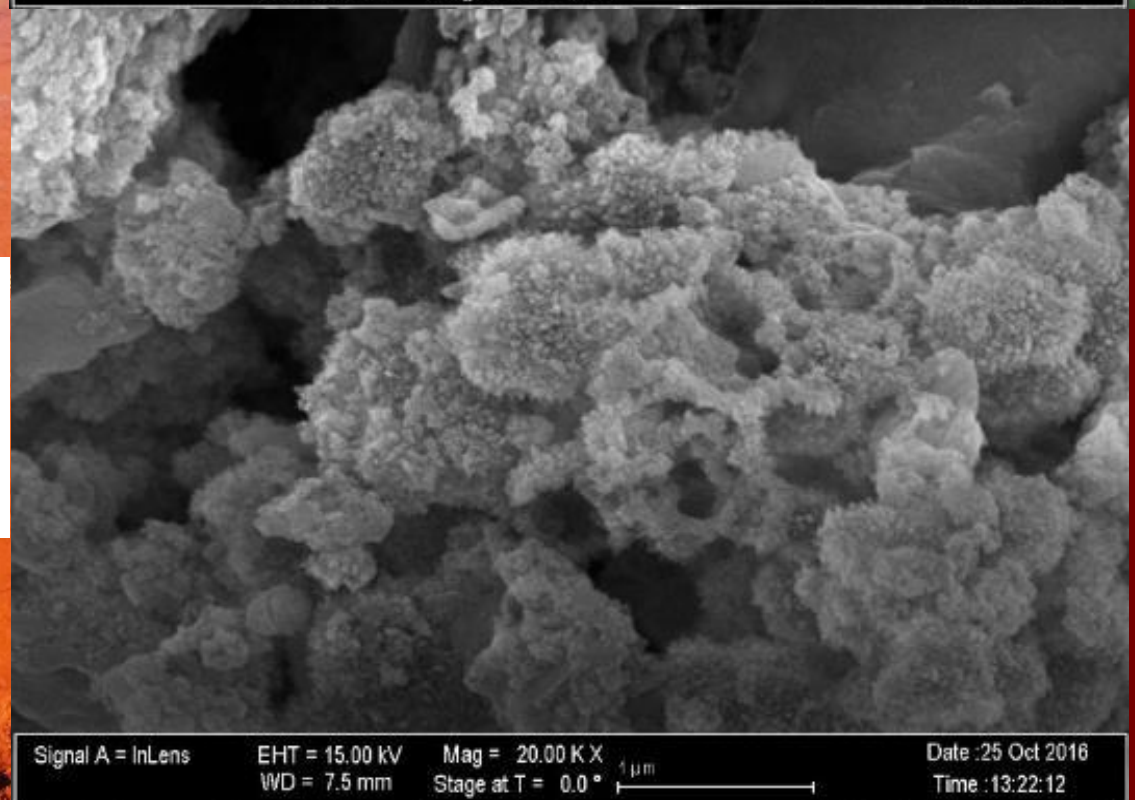


MRPTS Oxidation Pond during managed drawdown

Amorphous ferrihydrite typical of surface samples

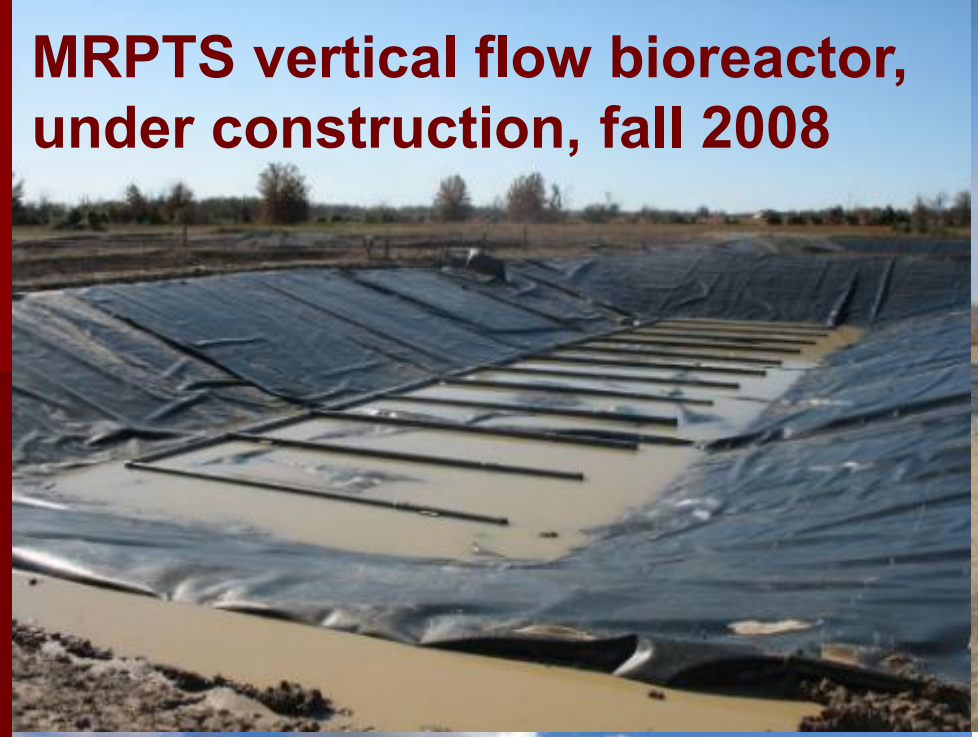
Goethite crystallization typical in deeper iron oxide samples





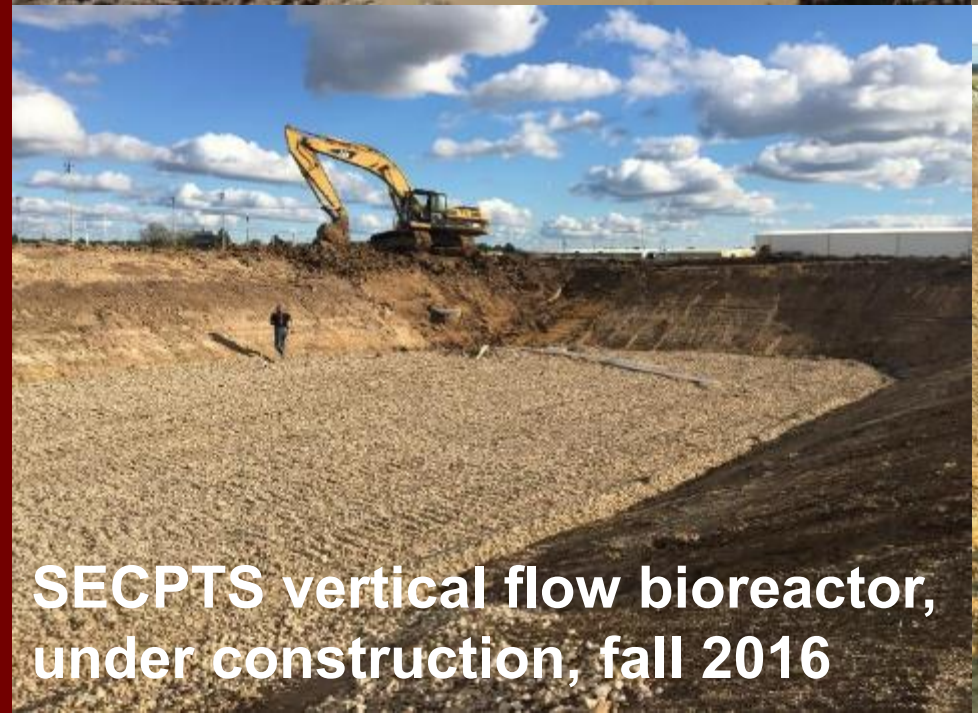
Reductive Processes

- Promote bacterial sulfate reduction
- Using mushroom compost
- Retention of Zn, Pb, Cd, Ni as sulfides

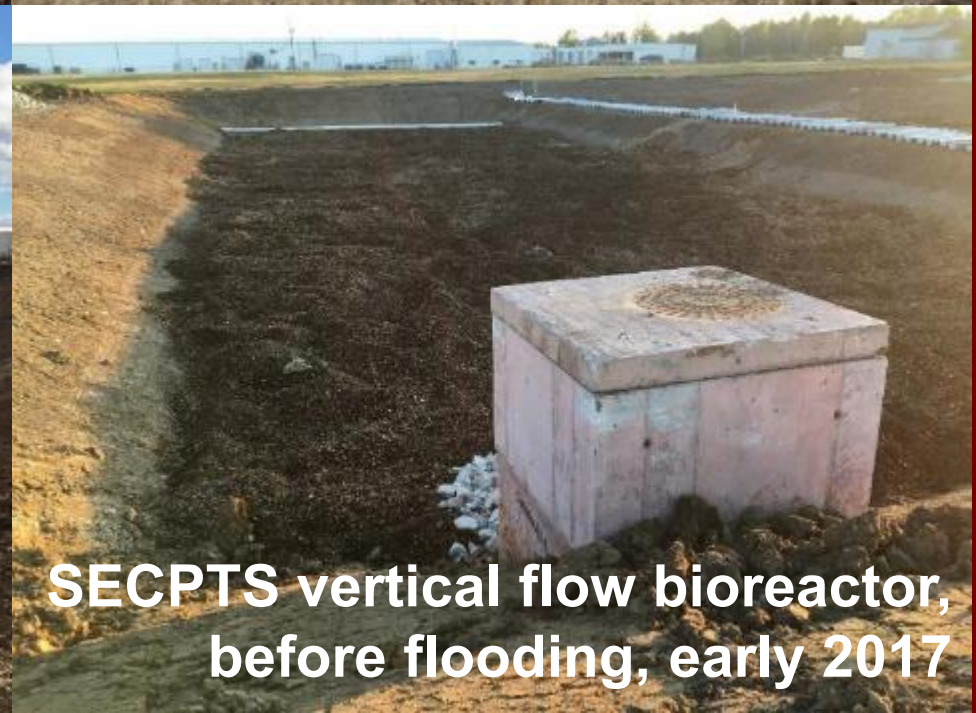


MRPTS vertical flow bioreactor, under construction, fall 2008

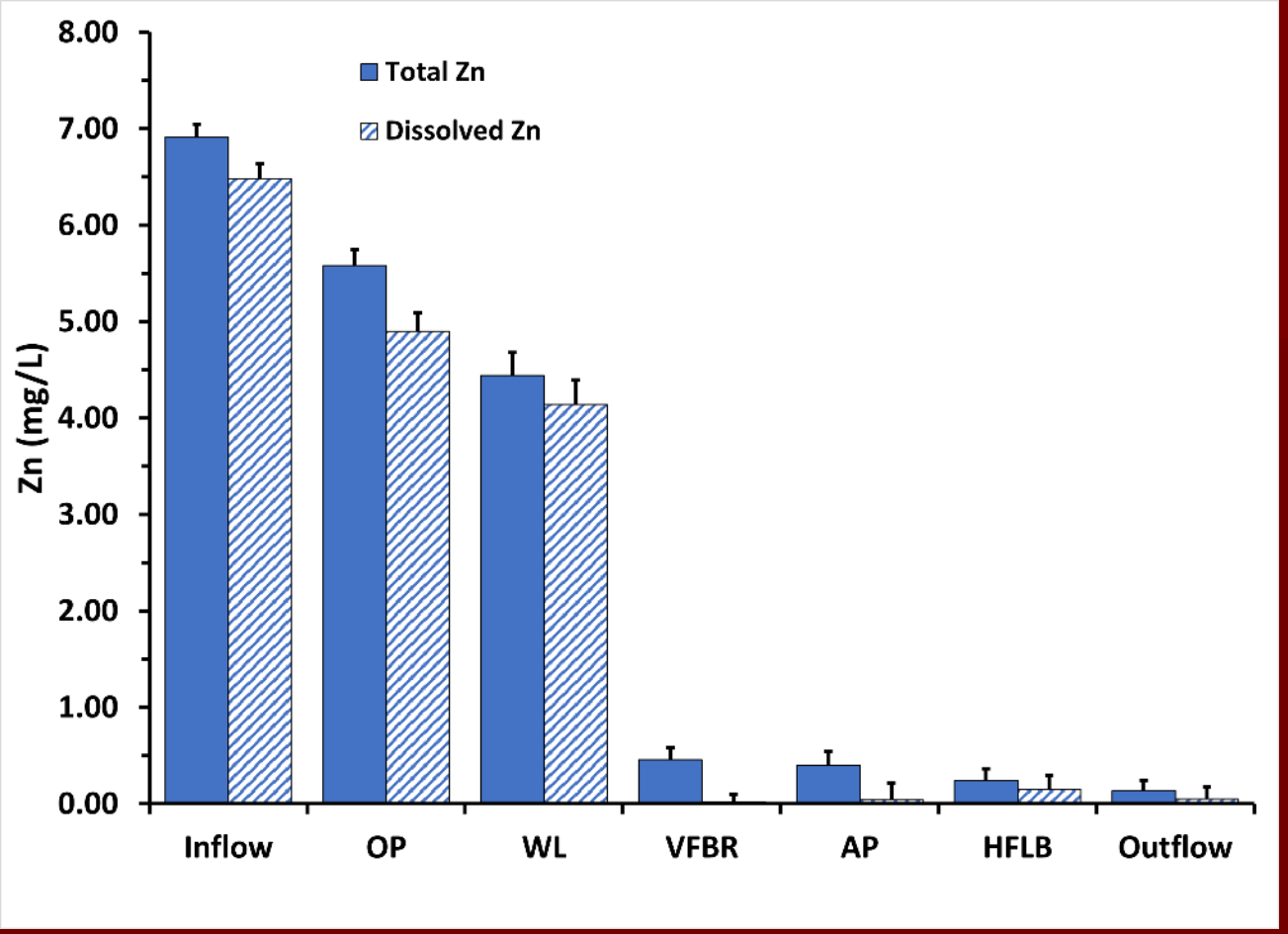
MRPTS vertical flow bioreactor, before flooding, fall 2008



SECPTS vertical flow bioreactor, under construction, fall 2016

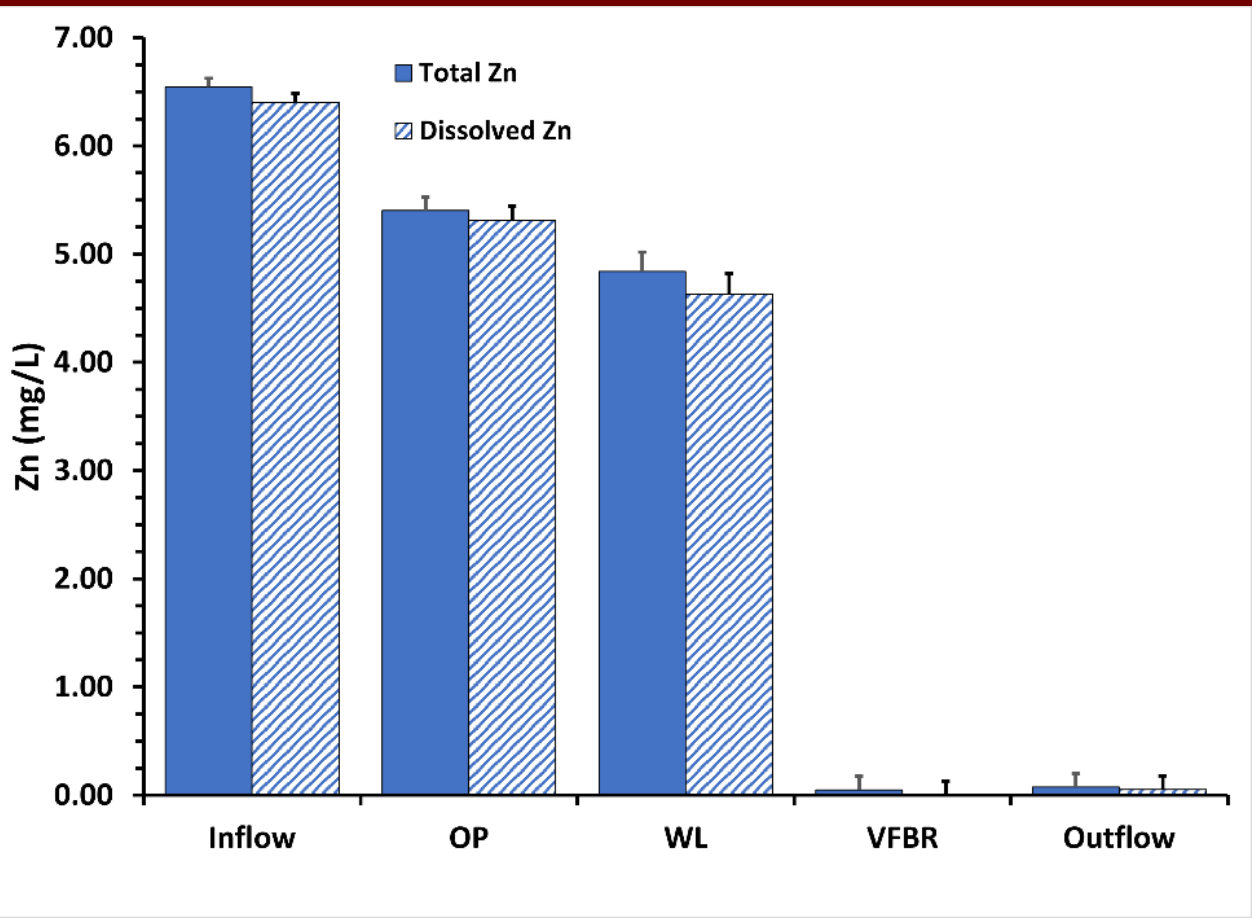


SECPTS vertical flow bioreactor, before flooding, early 2017



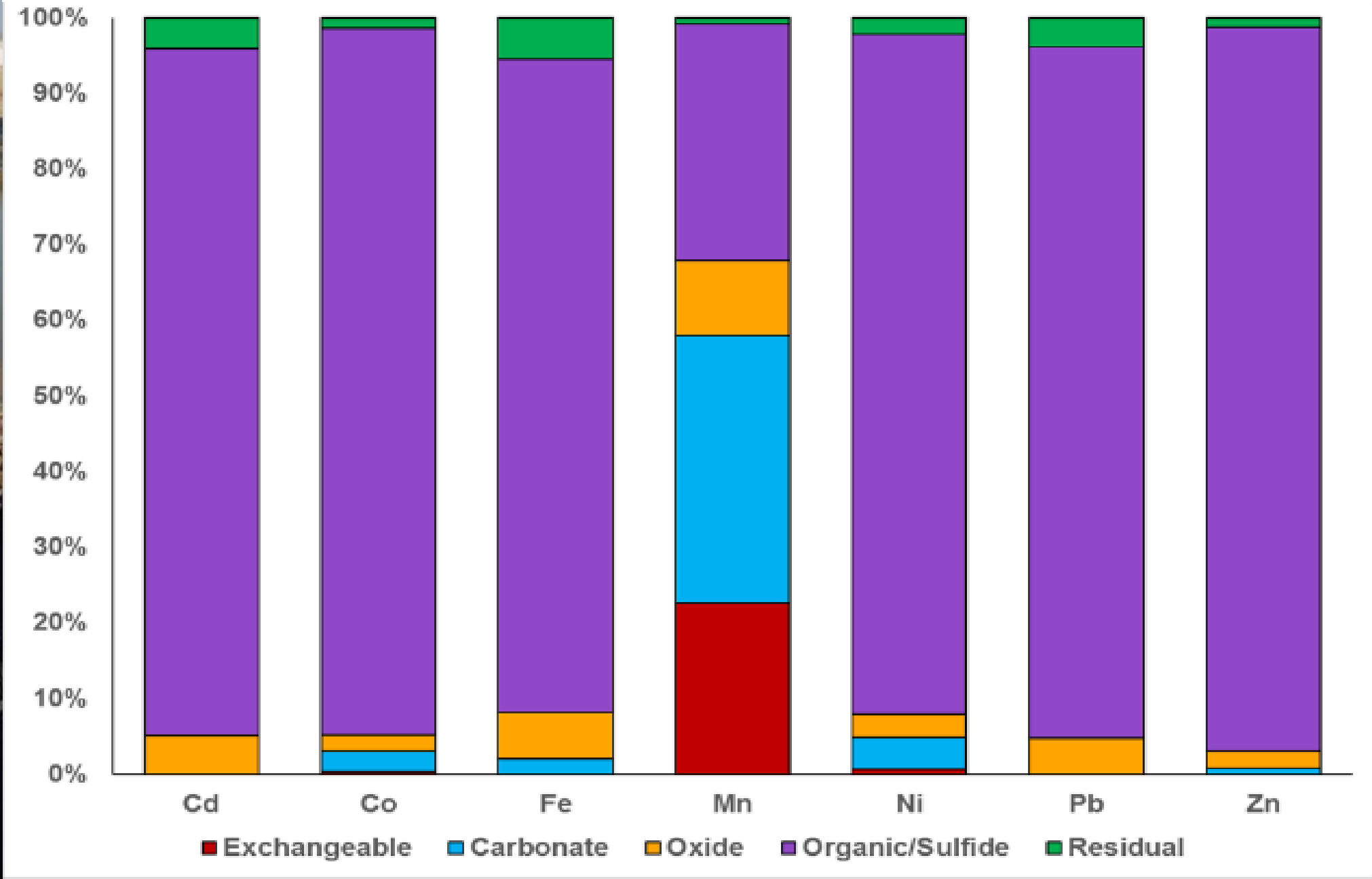
MRPTS Zn retention
2008-2022
(n=62)
Spent mushroom compost/
wood chips/ sand substrate

SECPTS Zn retention
2017-2022
(n=38)
Spent mushroom compost/
wood shavings substrate



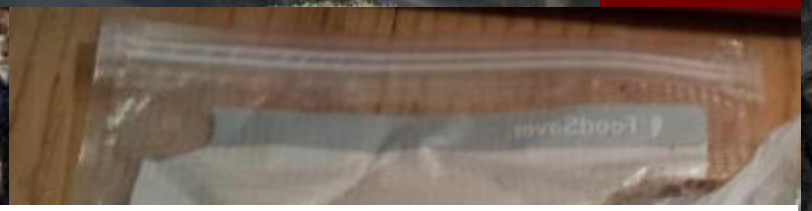
MRPTS Vertical F

VFBR Substrate Sequential Extractions

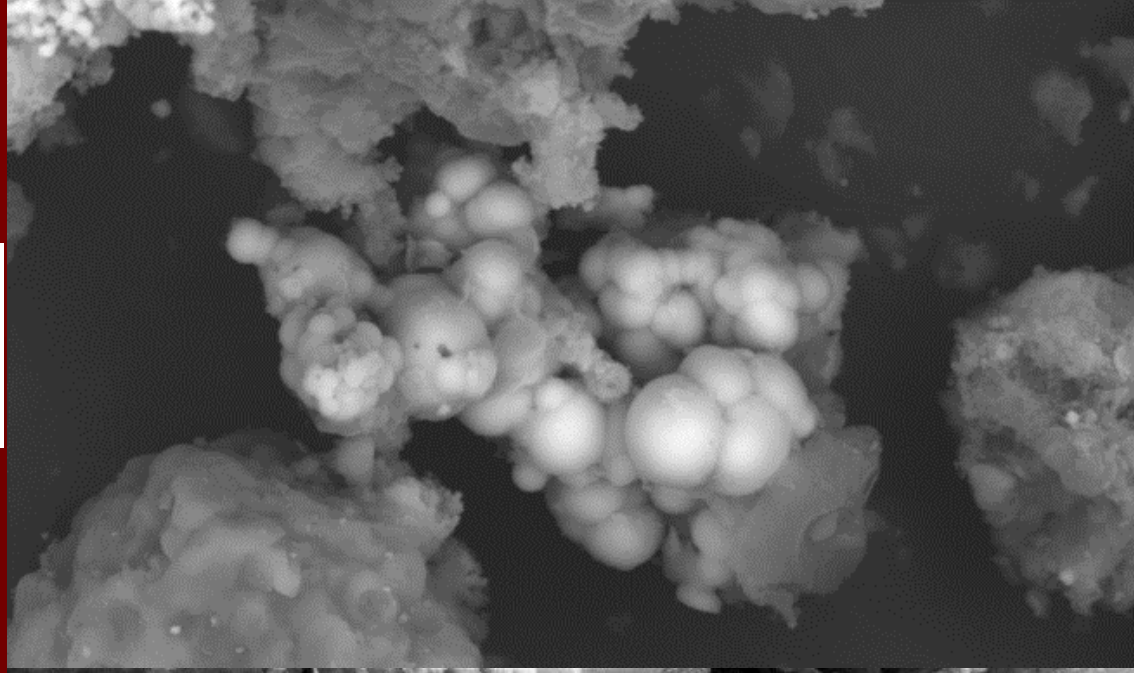


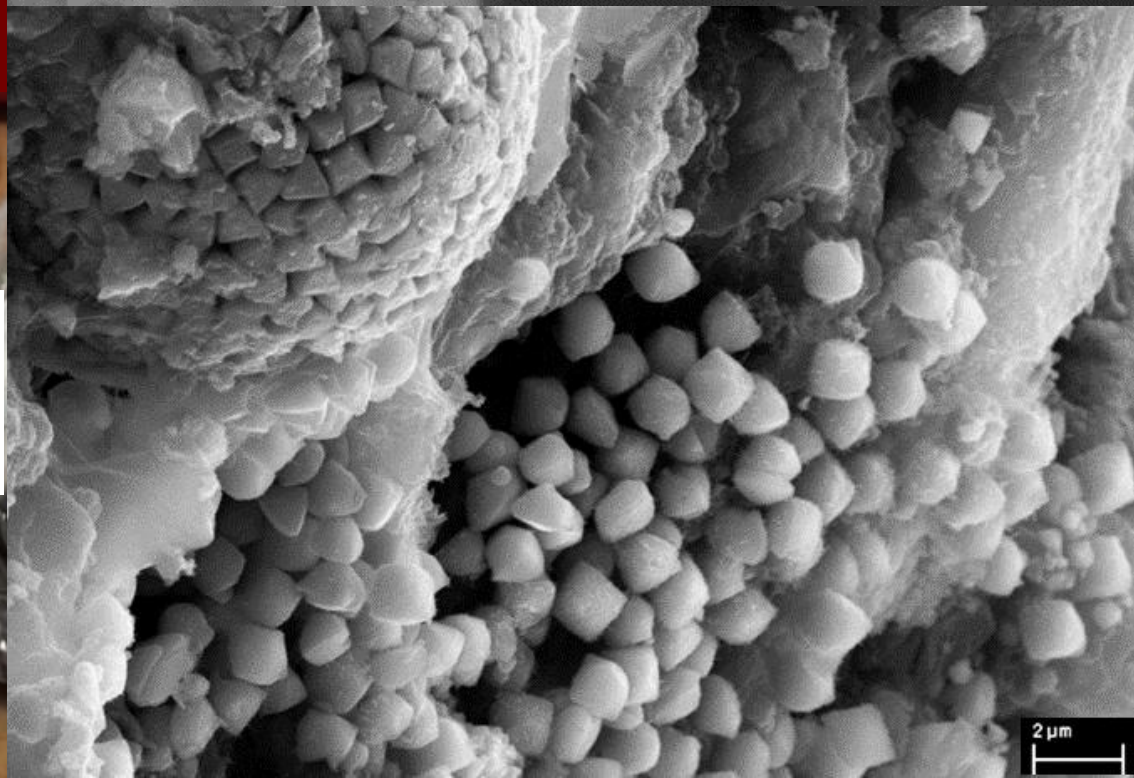
MRPTS Vertical Flow Bioreactor

Well-developed ZnS colloidal aggregates on humic materials in VFBR substrates



FeS_2 aggregation and framboidal pyrite in VFBR substrates



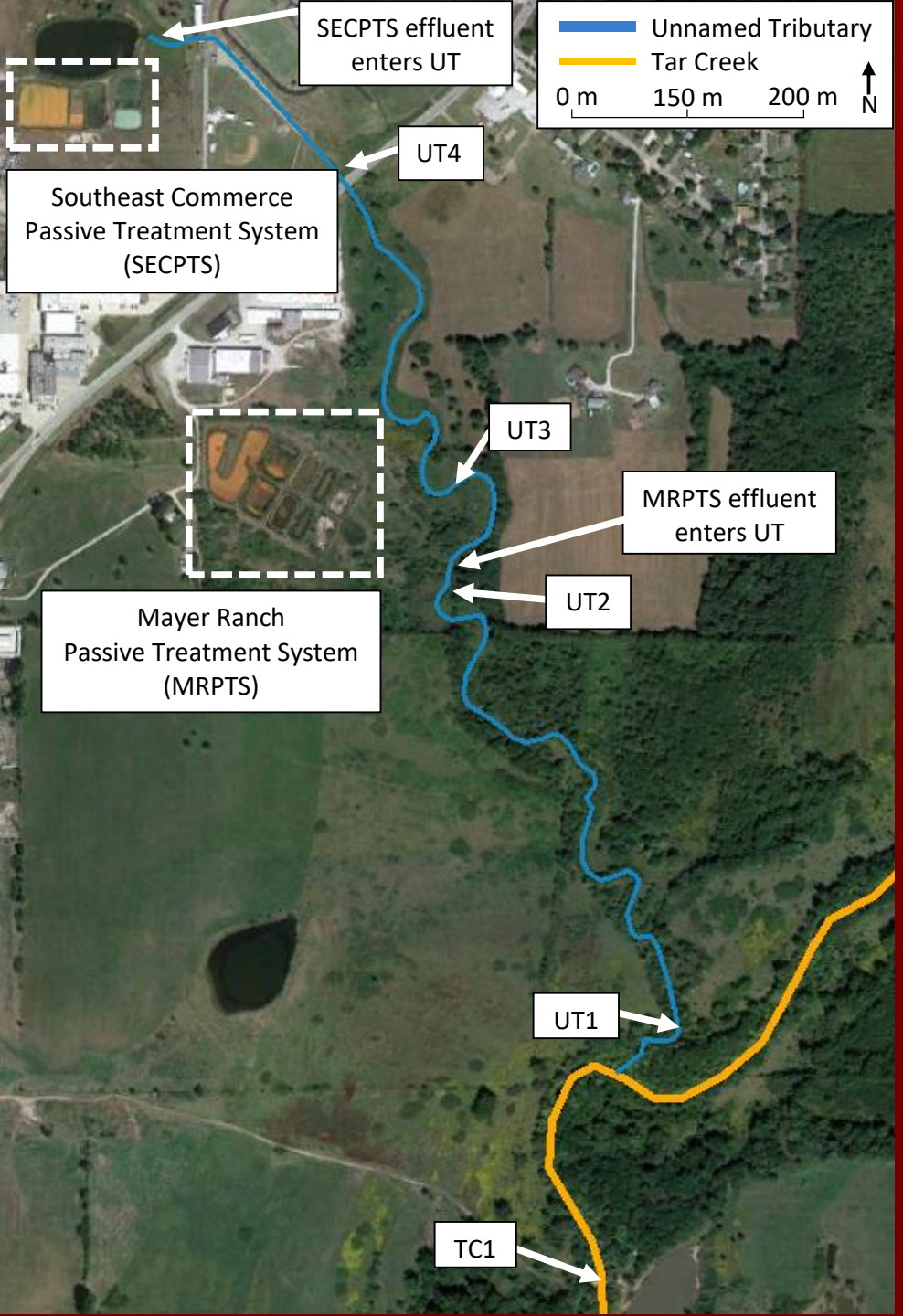


Some Design Innovations



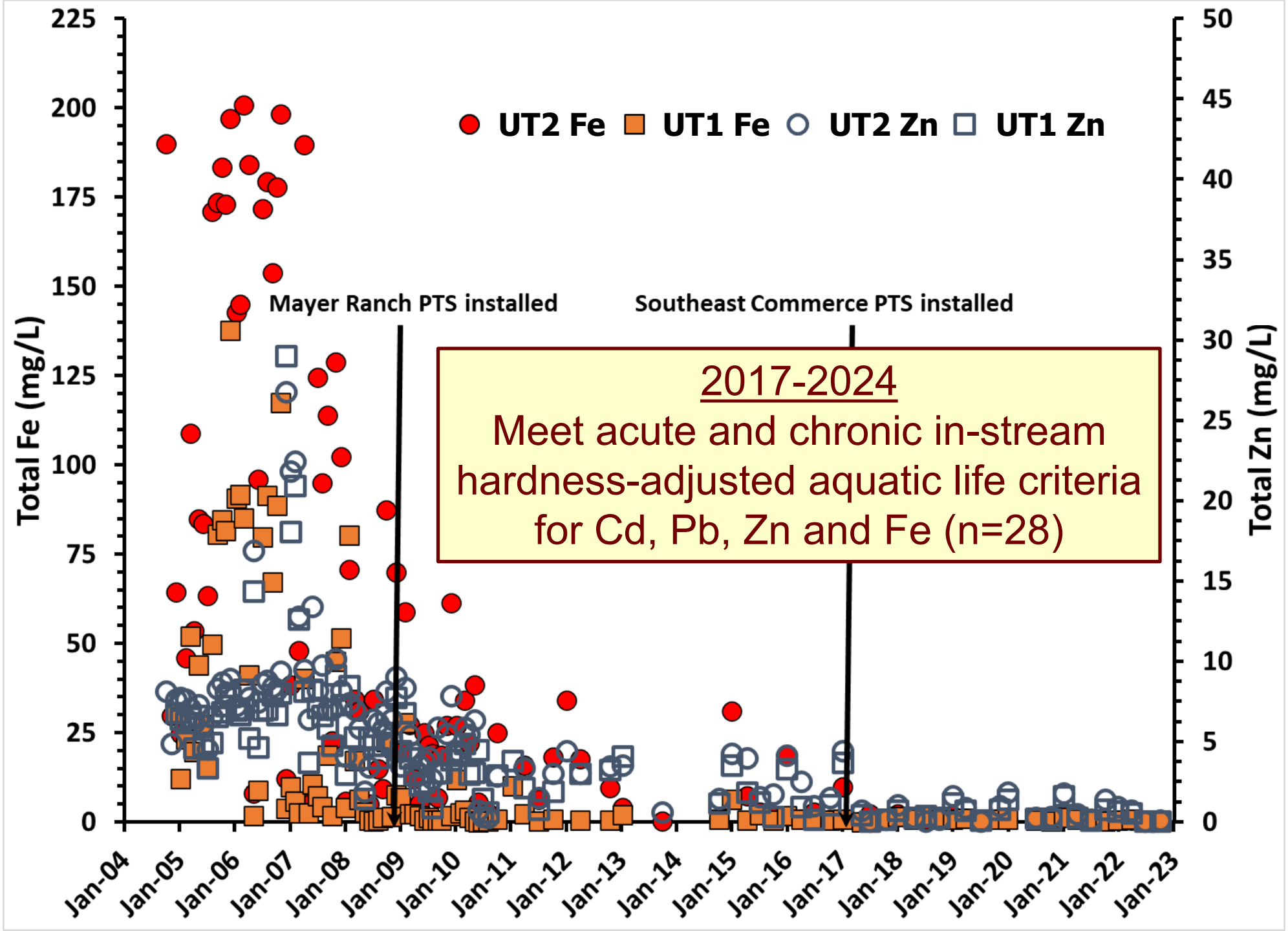
Pre-PTS
Post-PTS
Irreversibly Damaged?

3. Receiving Stream Recovery



Stream Sampling Sites

- UT4 - "Headwaters", downstream SEC
- UT3 - Downstream SEC
- UT2 - Downstream SEC and MR
- UT1 - Downstream SEC and MR
- TC1 - Downstream UT


UT2 Fe
UT1 Fe
UT2 Zn
UT1 Zn
Mayer Ranch PTS installed
Southeast Commerce PTS installed
2017-2024
Meet acute and chronic in-stream hardness-adjusted aquatic life criteria for Cd, Pb, Zn and Fe (n=28)
Total Fe (mg/L)
Total Zn (mg/L)
225
200
175
150
125
100
75
50
25
0
50
45
40
35
30
25
20
15
10
5
0
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15
Jan-16
Jan-17
Jan-18
Jan-19
Jan-20
Jan-21
Jan-22
Jan-23


07/19/2012

Unnamed Tributary fish data

Average CPUE UT-1 location

Species	2005-2007	2008	2009-2021
Western Mosquitofish	72.52		43.54
Green Sunfish	2.64		6.14
Bluegill Sunfish	0.29		7.49
Blackstripe Topminnow	0.14		21.22
Slough Darter	0.19		0.35
Black Bullhead Catfish	0.05		
River Carpsucker	0.04		
Golden Shiner	0.10		
Bluntnose Darter			0.04
Brook Silversides			0.09
Warmouth Sunfish			0.43
Orangespotted Sunfish			0.83
Longear Sunfish			3.22
Redear Sunfish			1.20
Largemouth Bass			0.56
White Crappie			0.04
Black Crappie			0.04
Hybrid Sunfish			0.26
Species Richness	**8**		**15**

MRPTS Construction

Unnamed Tributary fish data

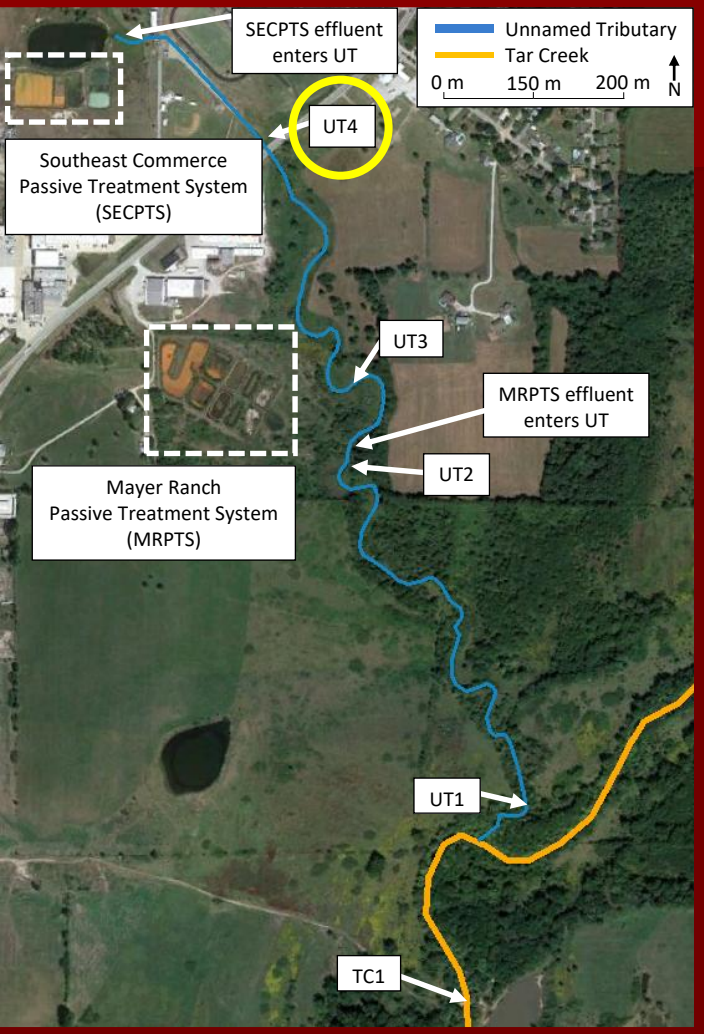
Average CPUE UT4 location

Species	2014-2016	2017	2017-2022
Western Mosquitofish	18.71		27.31
Bluegill Sunfish	0.57		100.92
Green Sunfish	0.29		13.38
Largemouth Bass	0.14		2.69
Longear Sunfish			6.23
Redear Sunfish			3.15
Golden Shiner			3.00
Blackstripe Topminnow			2.31
Black Crappie			1.77
Warmouth Sunfish			1.38
Golden Redhorse			1.08
Black Bullhead Catfish			0.92
Carmine Shiner			0.31
Gizzard Shad			0.23
Central Stoneroller			0.08
Common Carp			0.08
Brook Silversides			0.08
Orange Throat Darter			0.08
Orangespotted Sunfish			0.08
Spotted Sucker			0.08
Species Richness	4		20

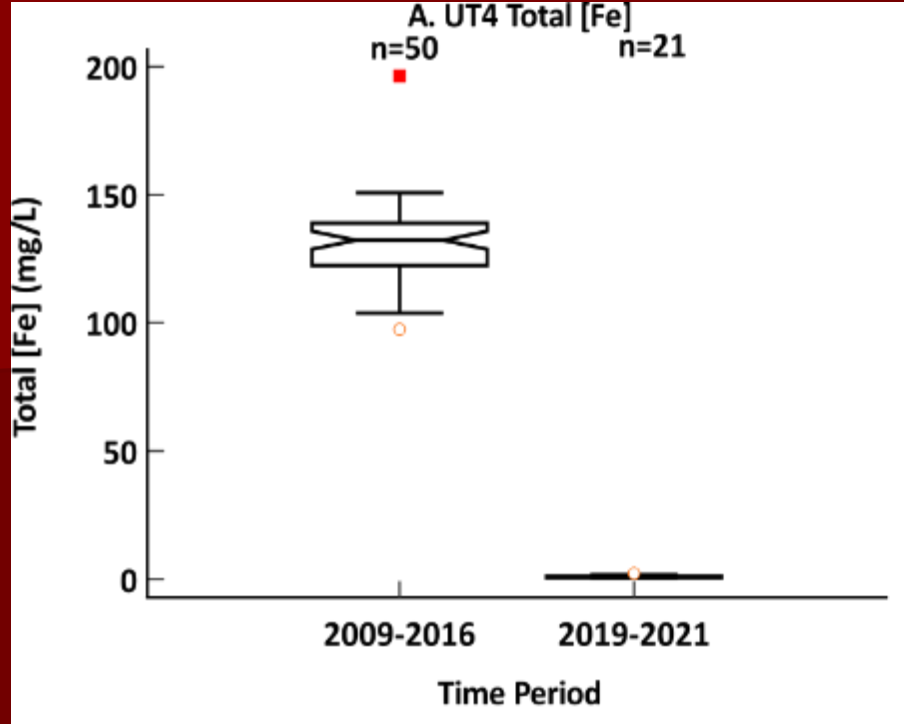
SECPTS Construction

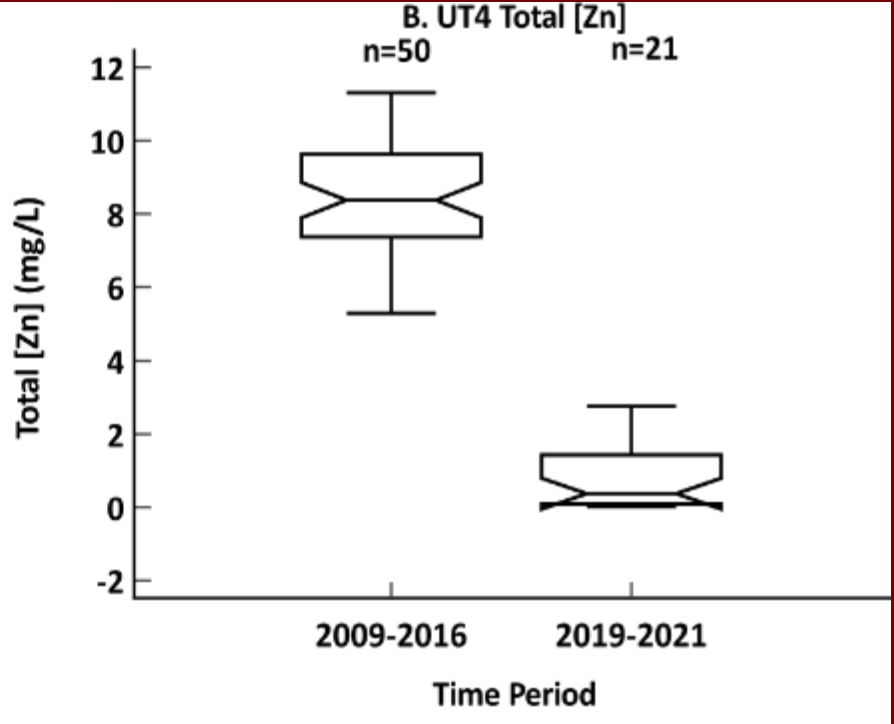
- No in-stream habitat restoration
- Only improvement of source water quality
- *Biotic integrity is restorable!*

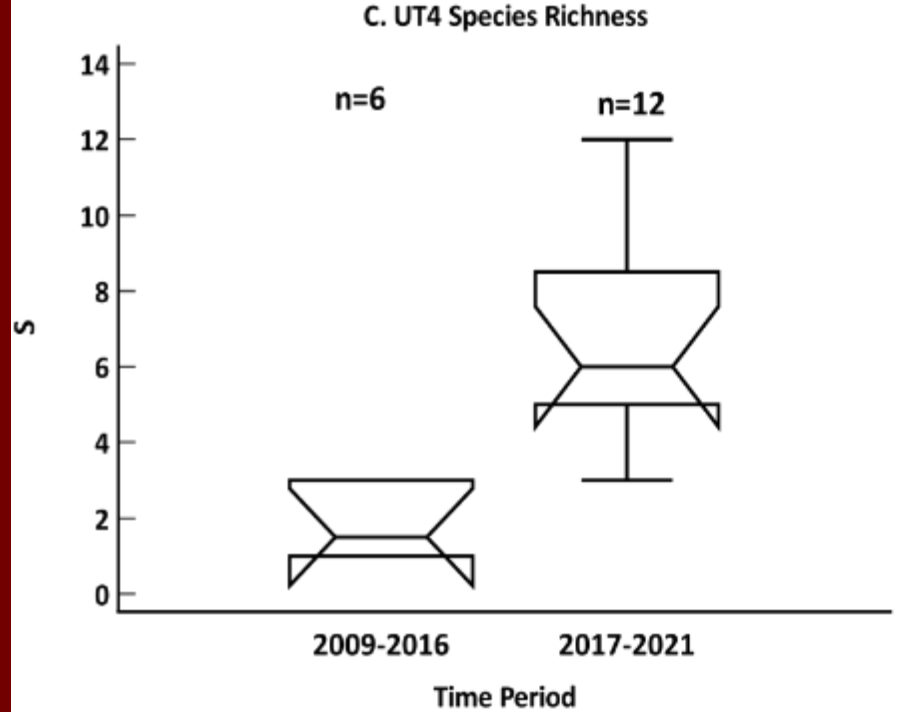
UT4

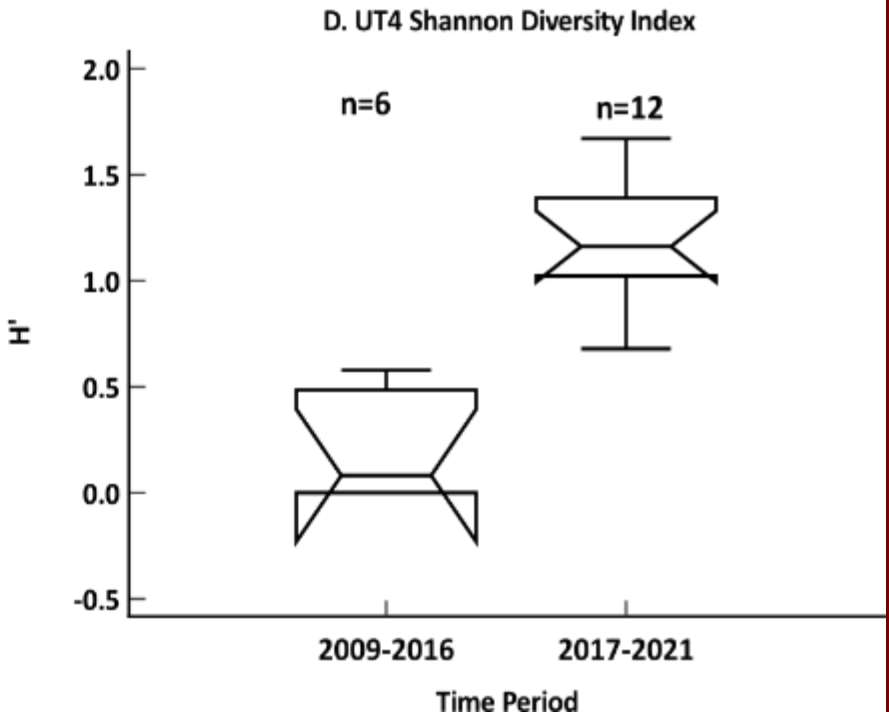


Not sampled prior to MRPTS construction

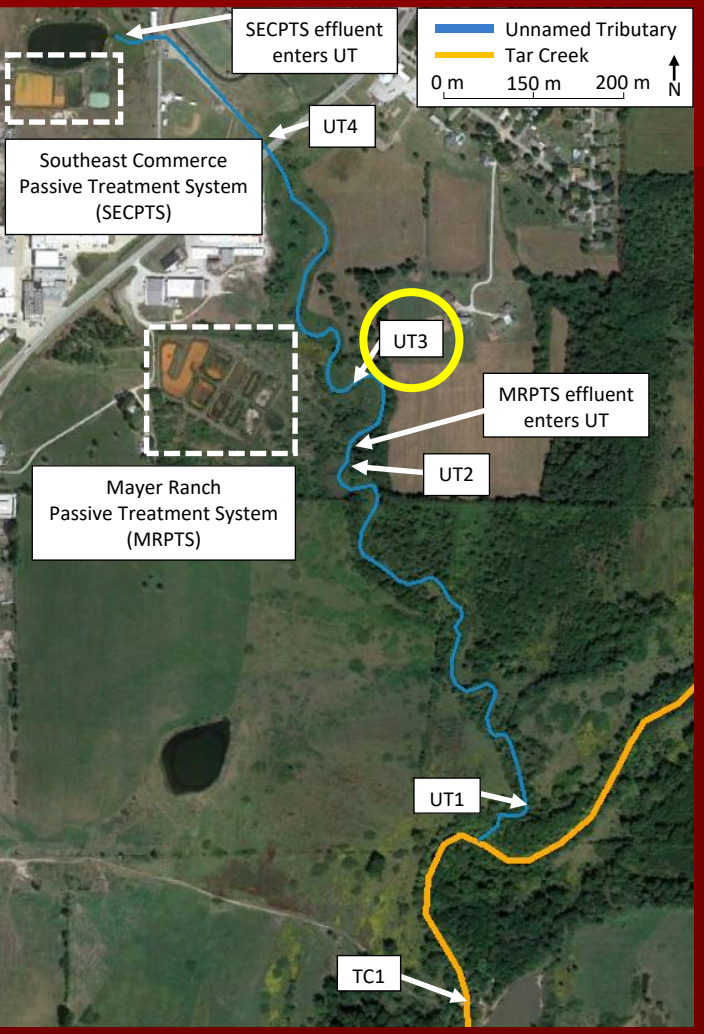


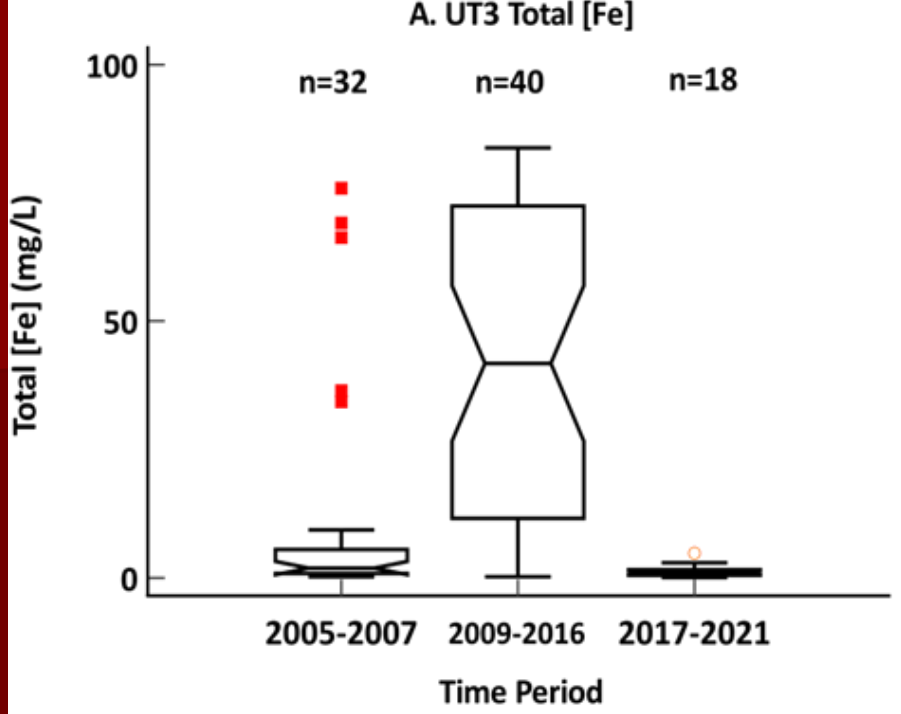


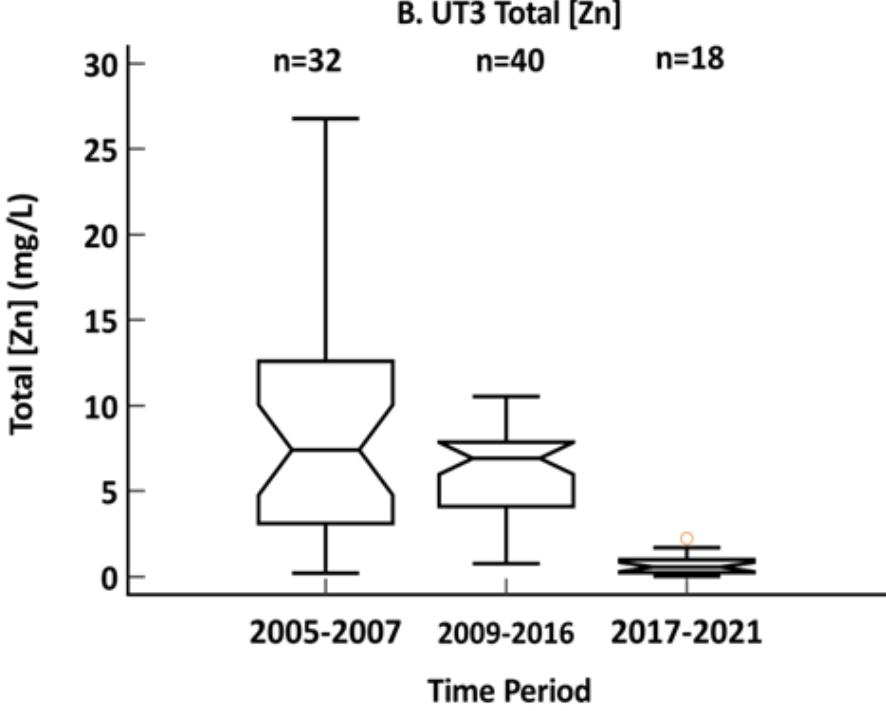


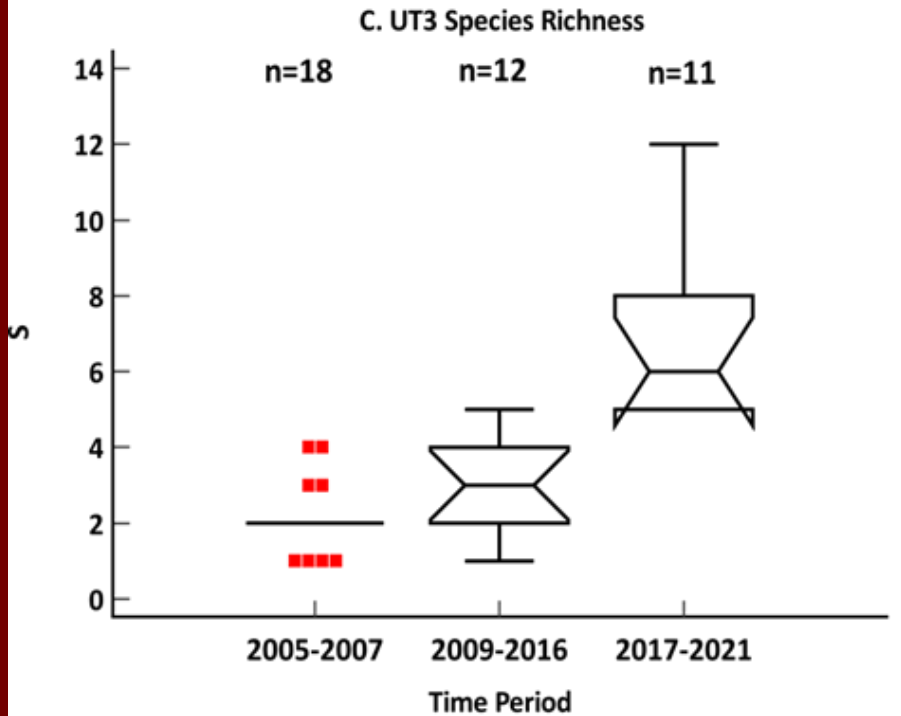


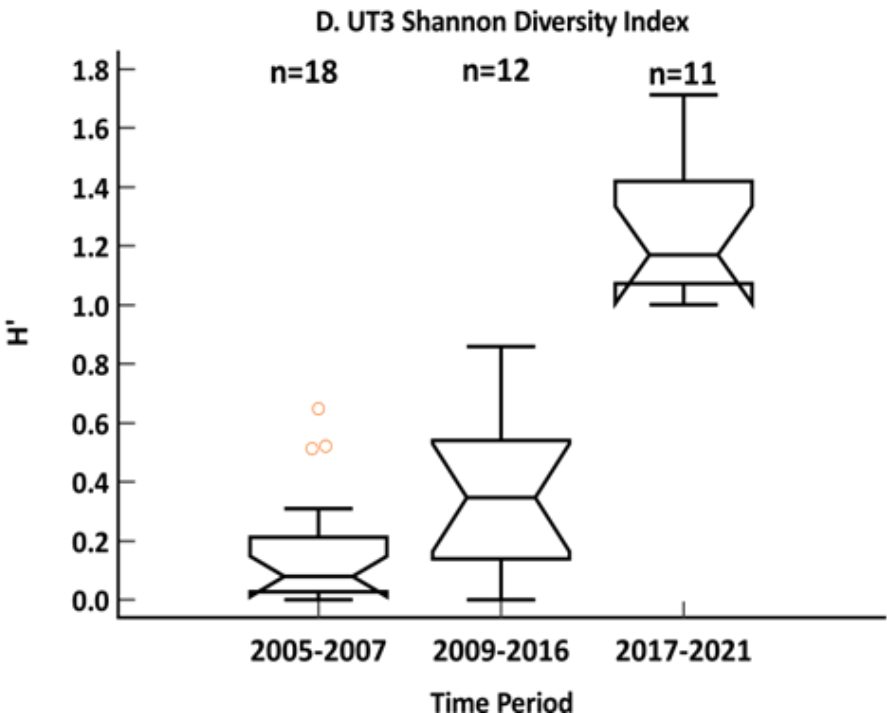
UT3


SECPTS effluent enters UT
Unnamed Tributary
Tar Creek
0 m
150 m
200 m
N
UT4
Southeast Commerce Passive Treatment System (SECPTS)
UT3
MRPTS effluent enters UT
UT2
Mayer Ranch Passive Treatment System (MRPTS)
UT1
TC1

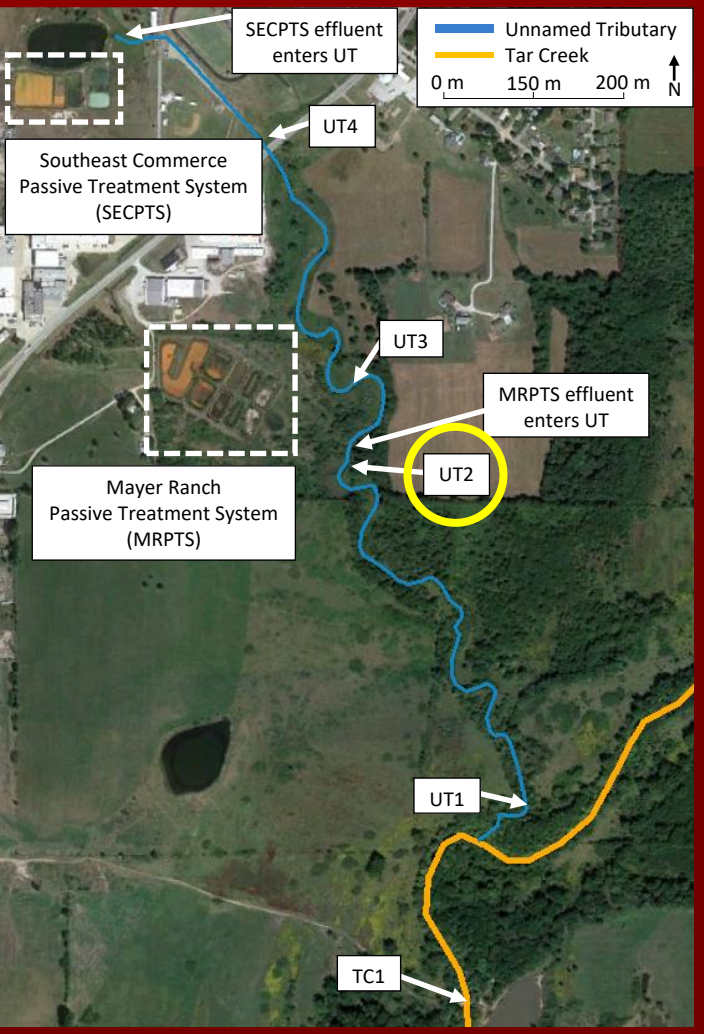

A. UT3 Total [Fe]
Total [Fe] (mg/L)
100
50
0
n=32
n=40
n=18
2005-2007
2009-2016
2017-2021
Time Period


B. UT3 Total [Zn]
Total [Zn] (mg/L)
30
25
20
15
10
5
0
n=32
n=40
n=18
2005-2007
2009-2016
2017-2021
Time Period

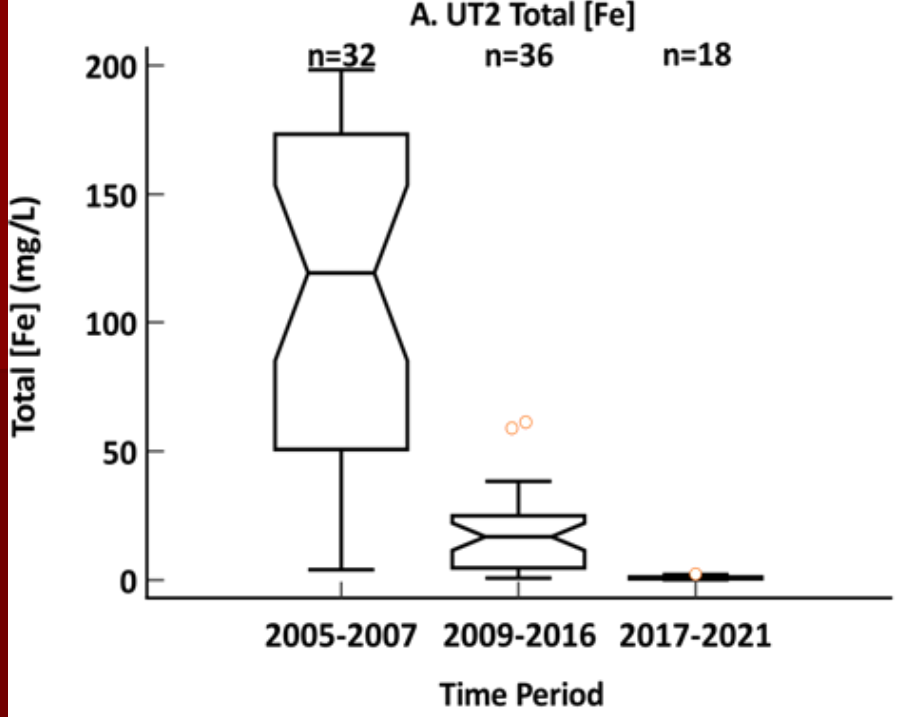

C. UT3 Species Richness
S
14
12
10
8
6
4
2
0
n=18
n=12
n=11
2005-2007
2009-2016
2017-2021
Time Period

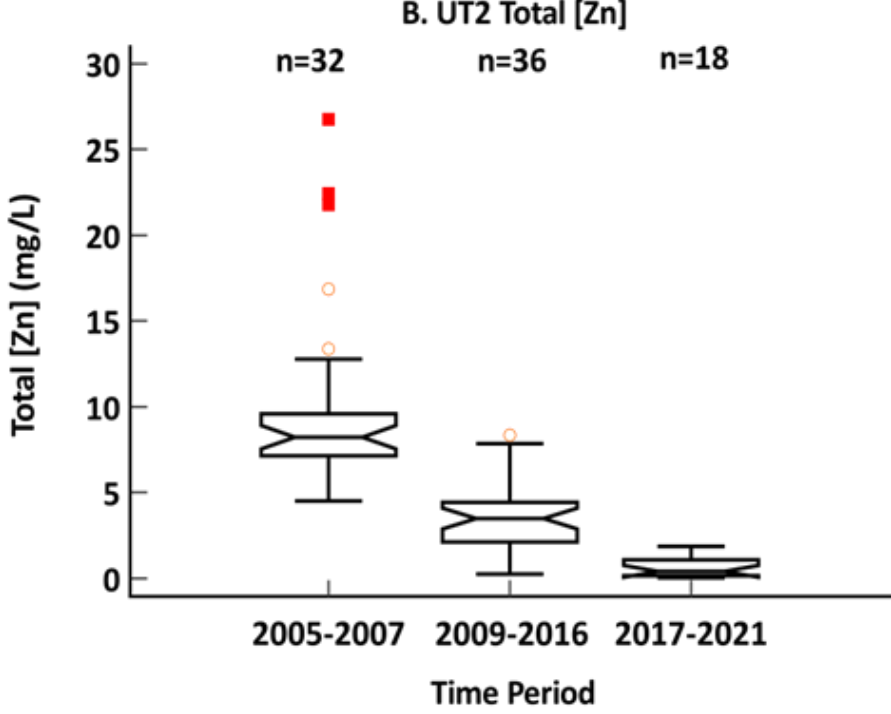

D. UT3 Shannon Diversity Index
H'
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
n=18
n=12
n=11
2005-2007
2009-2016
2017-2021
Time Period

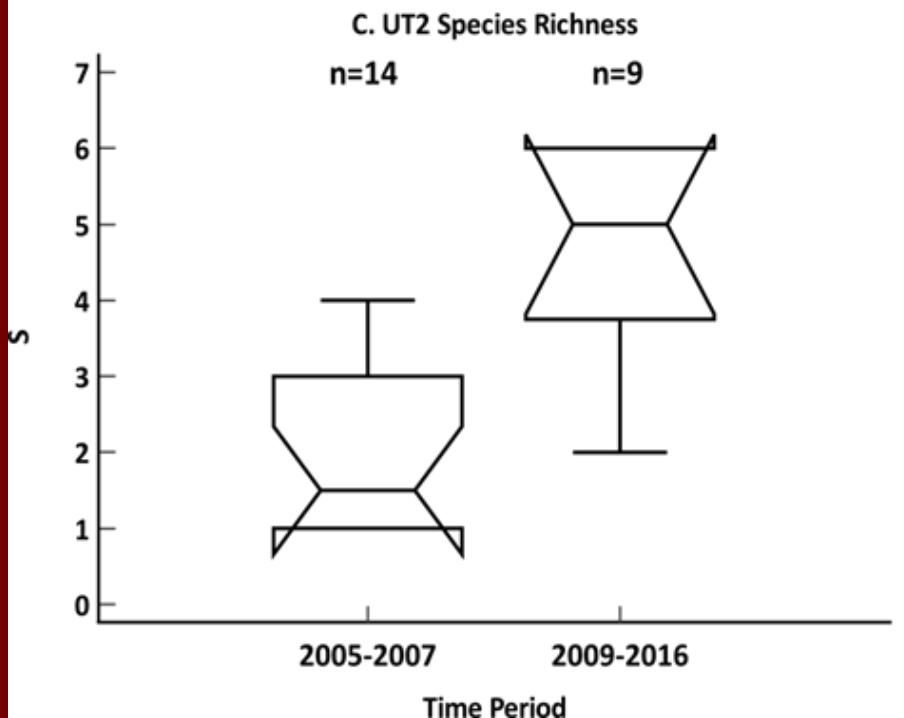
UT2

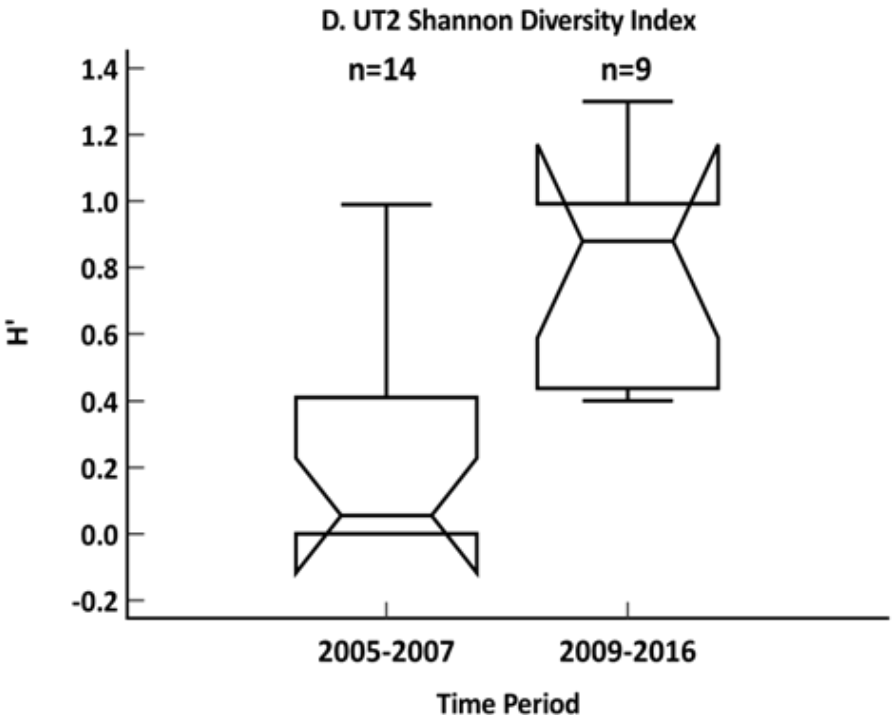


Fish sampling not practical after 2016

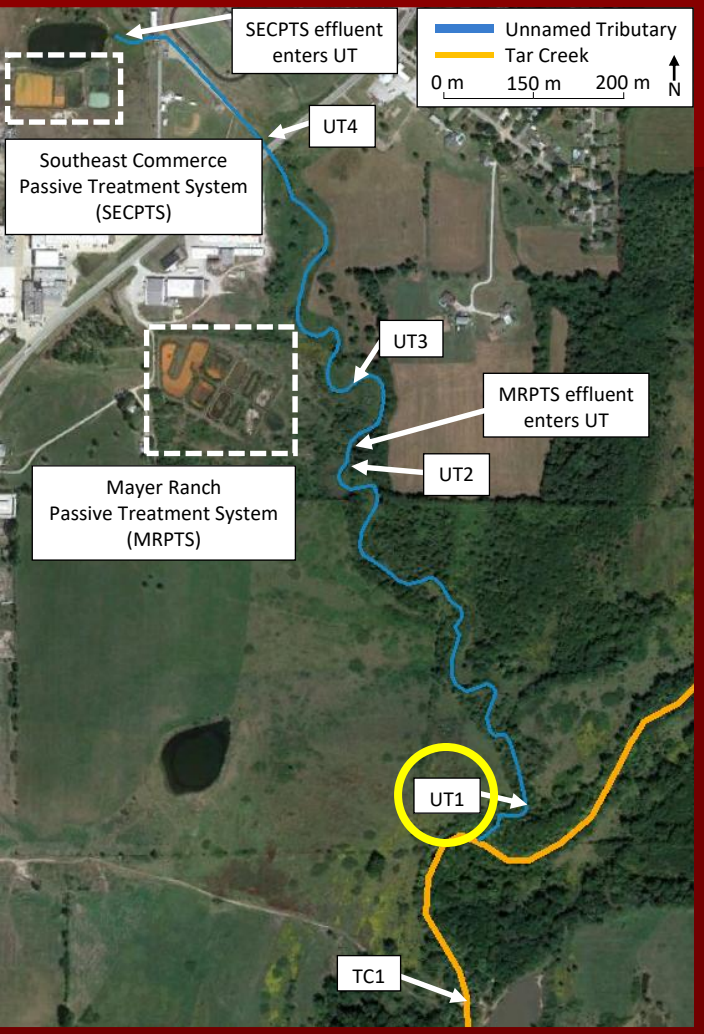


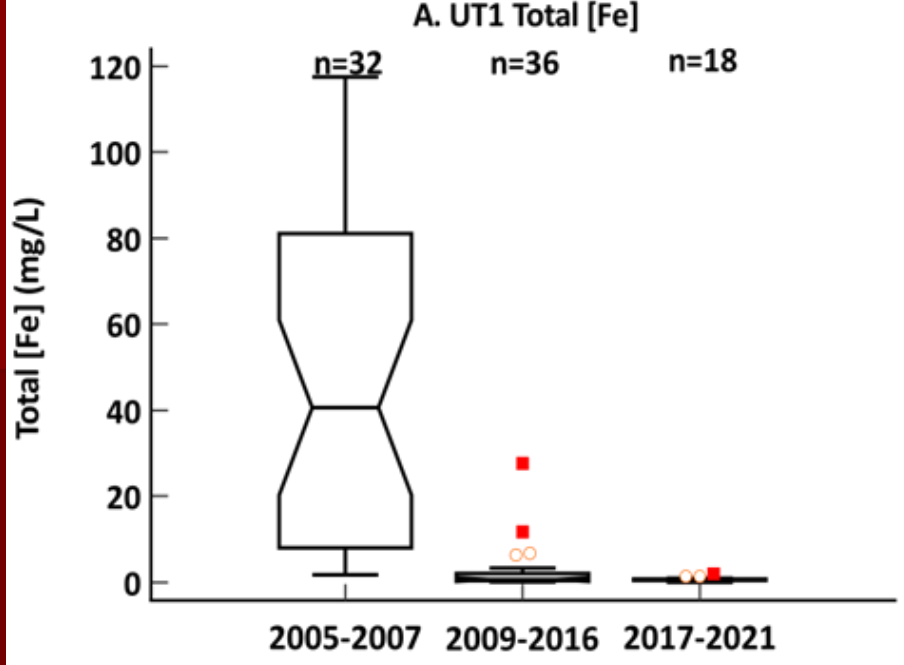


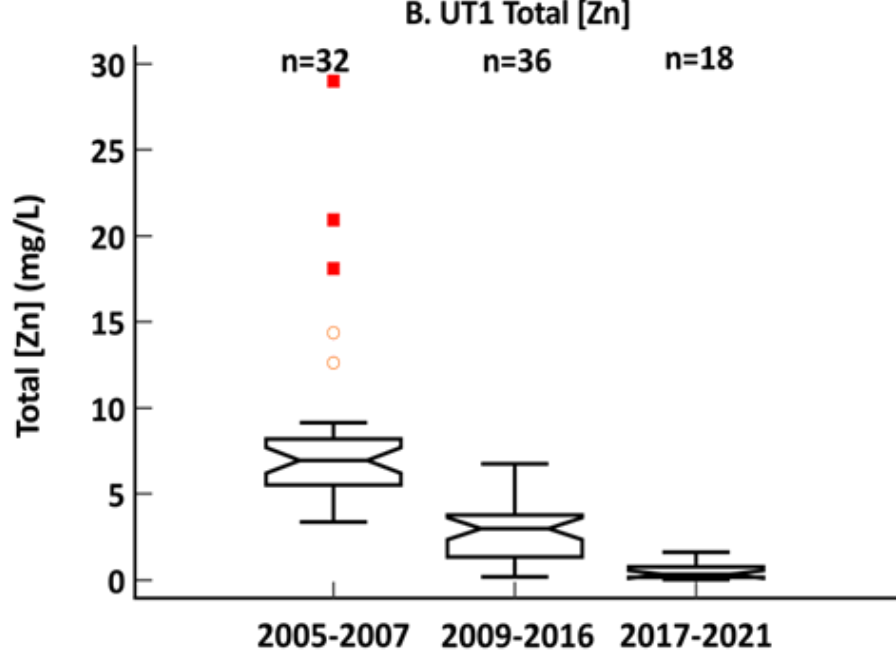


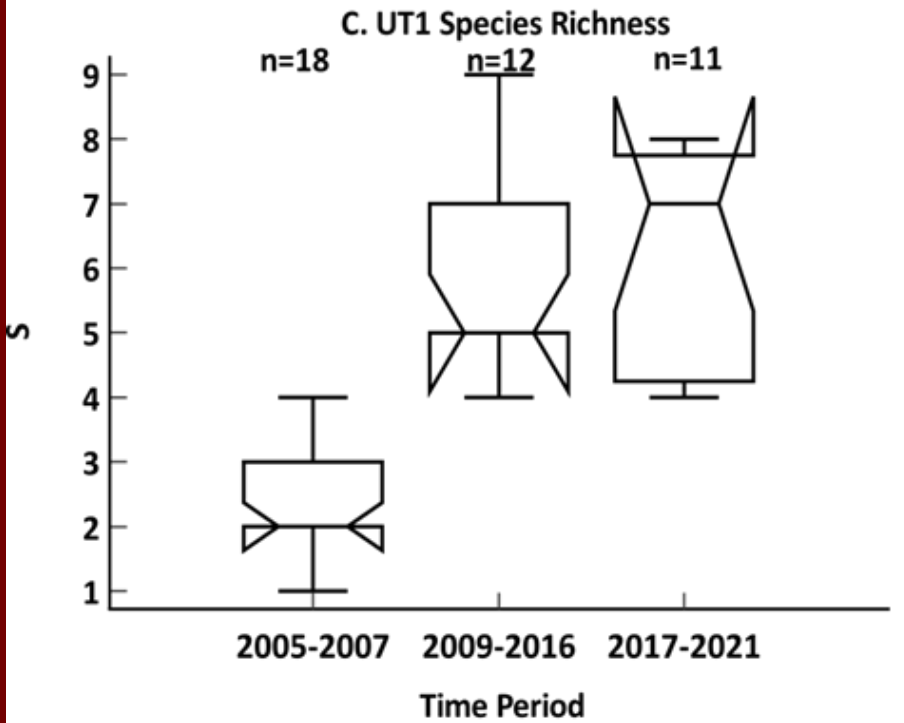


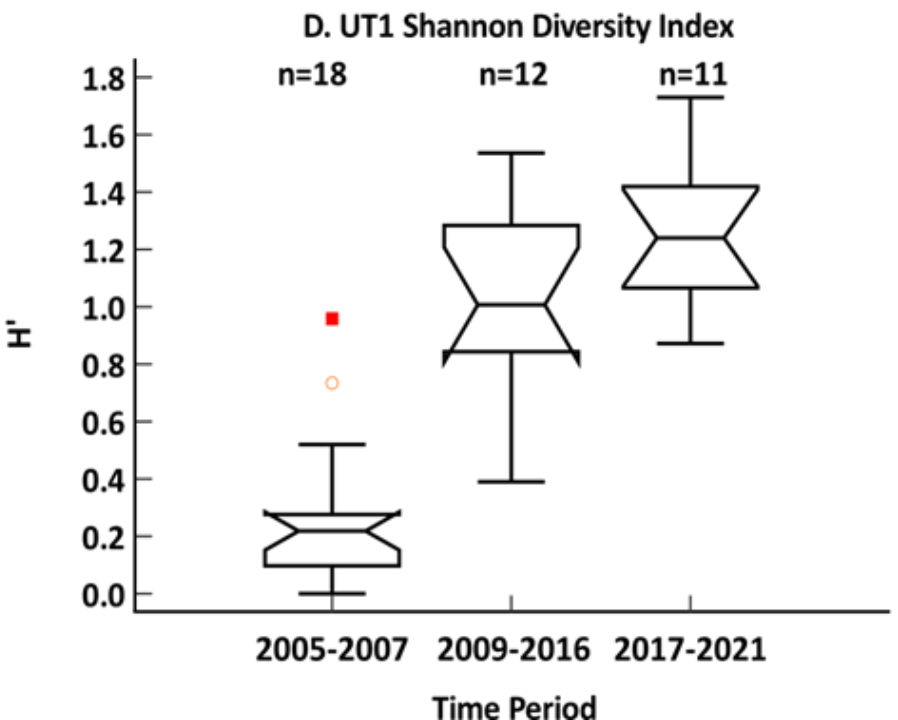
UT1

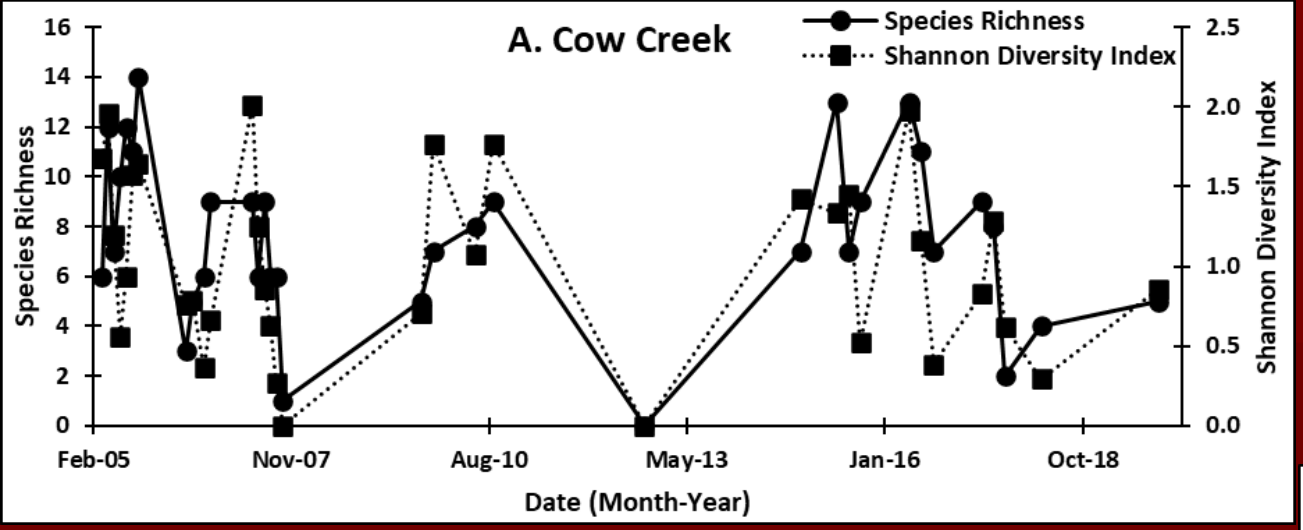

SECPTS effluent enters UT
Unnamed Tributary
Tar Creek
0 m
150 m
200 m
N
UT4
Southeast Commerce Passive Treatment System (SECPTS)
UT3
MRPTS effluent enters UT
UT2
Mayer Ranch Passive Treatment System (MRPTS)
UT1
TC1

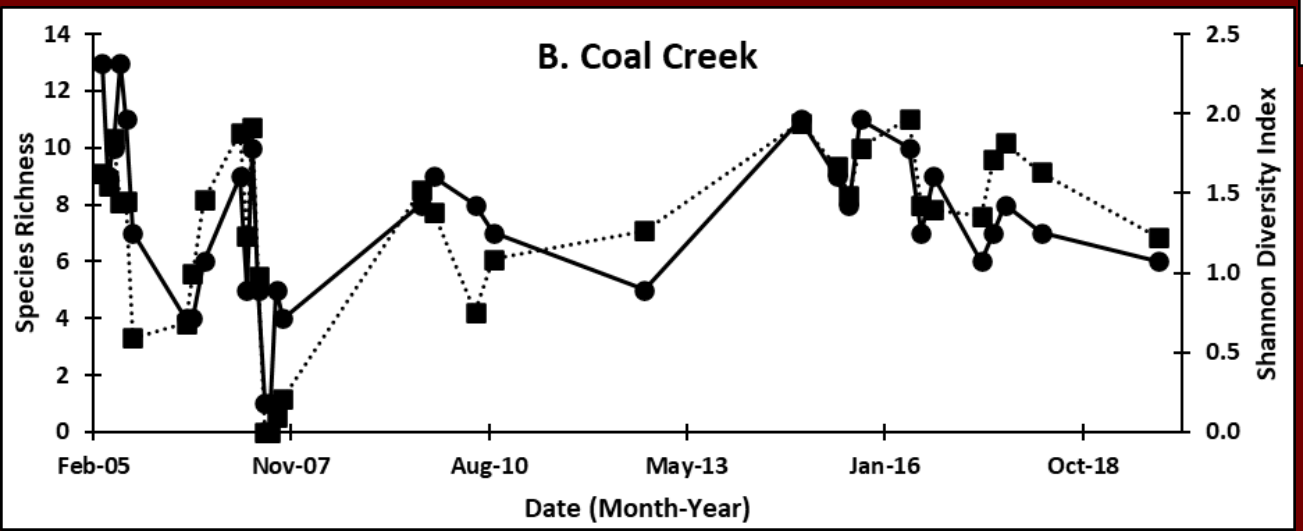

A. UT1 Total [Fe]
n=32
n=36
n=18
Total [Fe] (mg/L)
120
100
80
60
40
20
0
2005-2007
2009-2016
2017-2021
Time Period

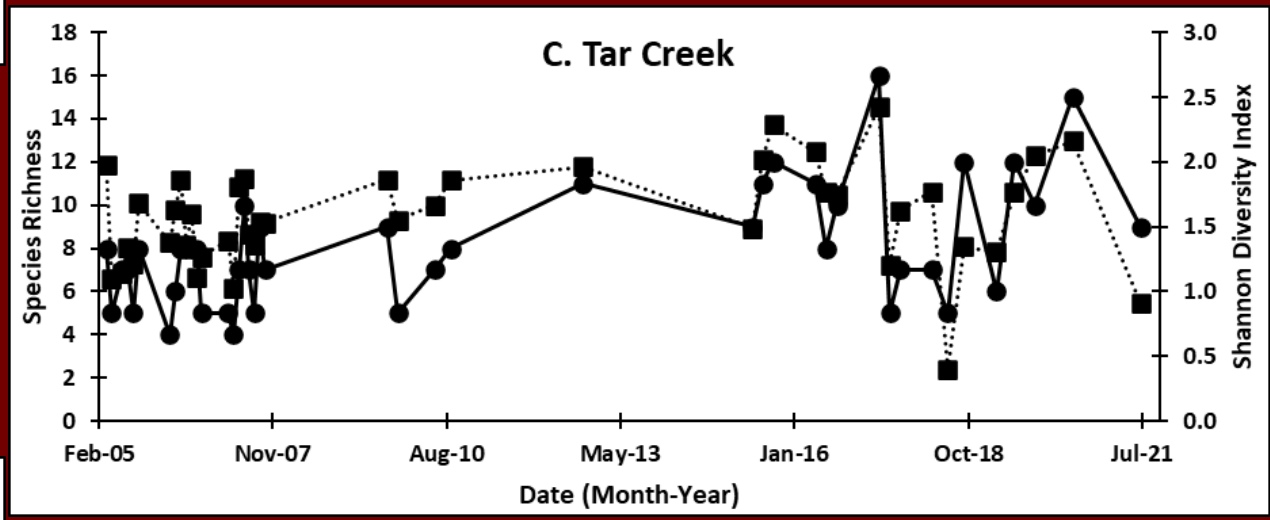

B. UT1 Total [Zn]
n=32
n=36
n=18
Total [Zn] (mg/L)
30
25
20
15
10
5
0
2005-2007
2009-2016
2017-2021
Time Period

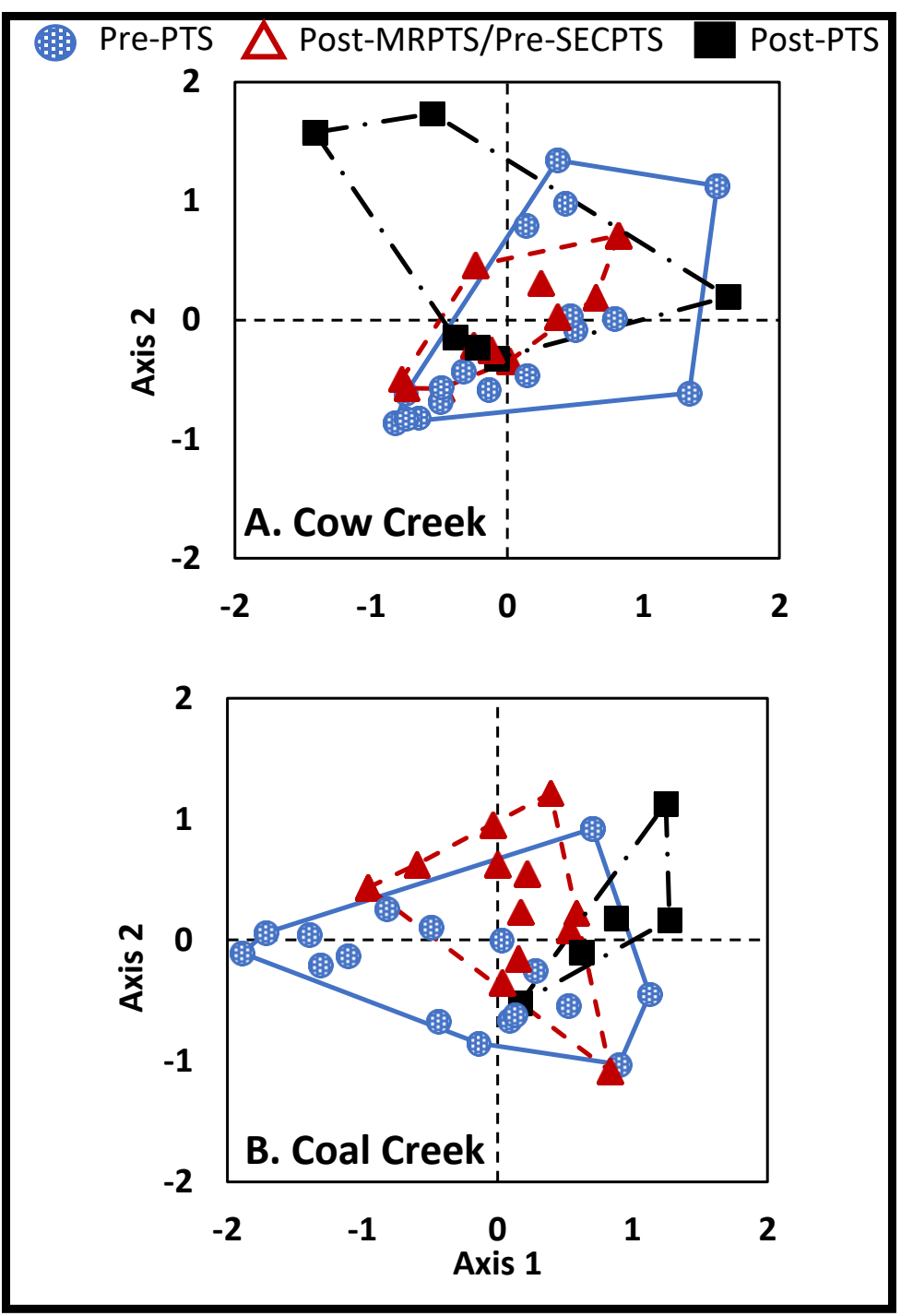

C. UT1 Species Richness
n=18
n=12
n=11
S
9
8
7
6
5
4
3
2
1
2005-2007
2009-2016
2017-2021
Time Period

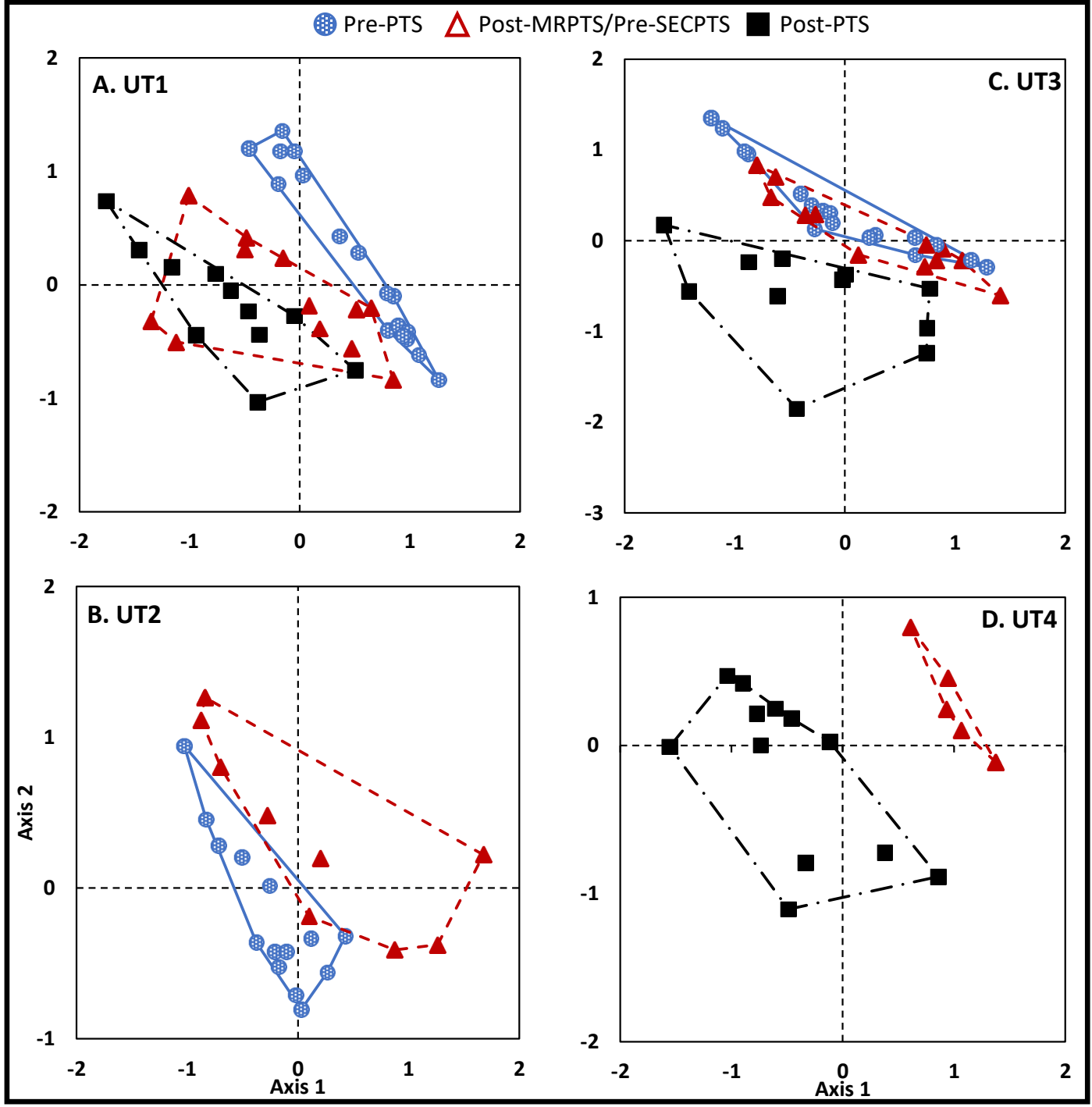

D. UT1 Shannon Diversity Index
n=18
n=12
n=11
H'
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2005-2007
2009-2016
2017-2021
Time Period


A. Cow Creek
Species Richness
Shannon Diversity Index
Species Richness
Shannon Diversity Index
Feb-05
Nov-07
Aug-10
May-13
Jan-16
Oct-18
Date (Month-Year)


B. Coal Creek
Species Richness
Shannon Diversity Index
Feb-05
Nov-07
Aug-10
May-13
Jan-16
Oct-18
Date (Month-Year)

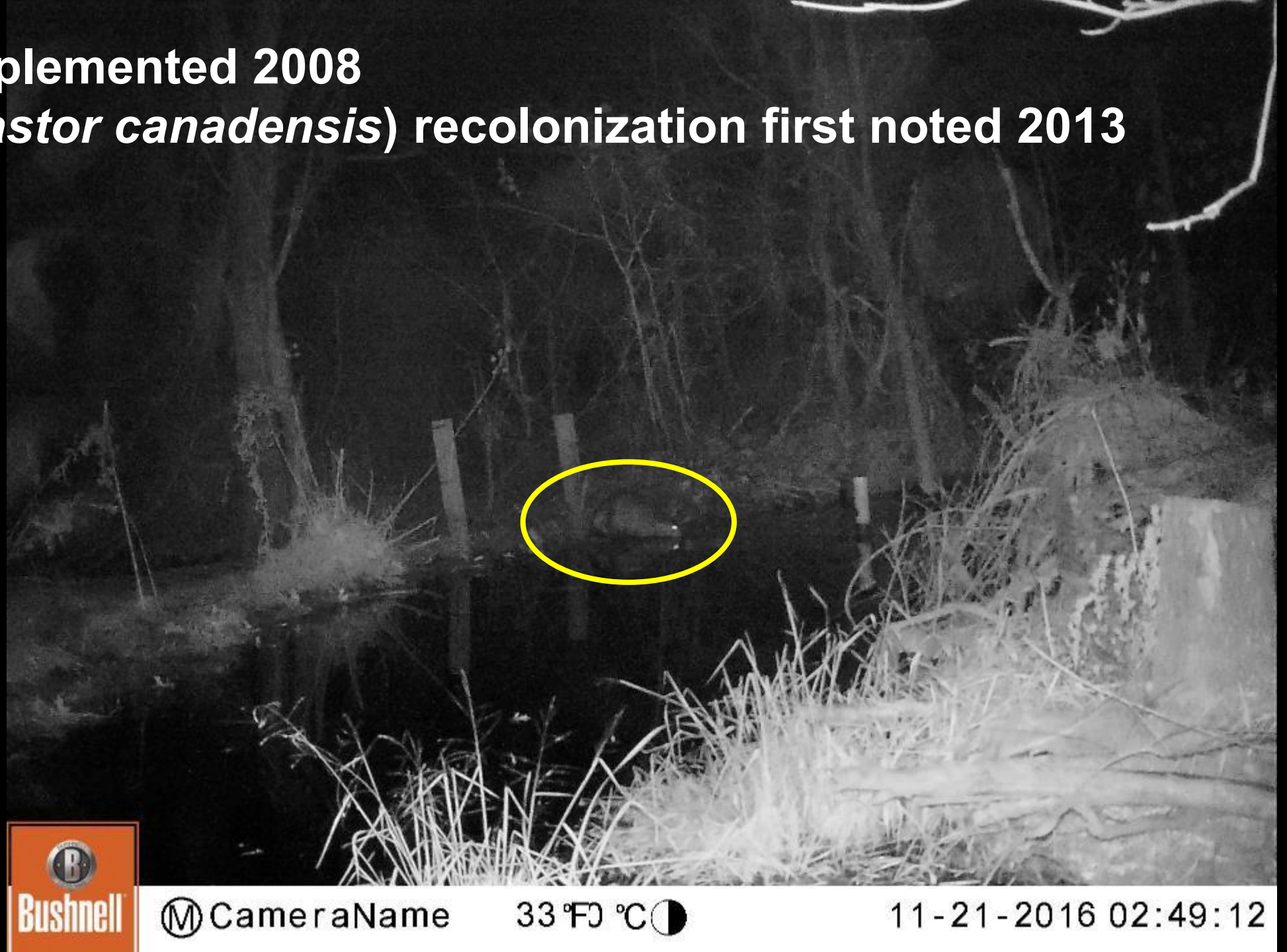

C. Tar Creek
Species Richness
Shannon Diversity Index
Feb-05
Nov-07
Aug-10
May-13
Jan-16
Oct-18
Jul-21
Date (Month-Year)


Pre-PTS
Post-MRPTS/Pre-SECPTS
Post-PTS
A. Cow Creek
B. Coal Creek
Axis 2
Axis 1


Pre-PTS
Post-MRPTS/Pre-SECPTS
Post-PTS
A. UT1
C. UT3
B. UT2
D. UT4
Axis 2
Axis 1


UT2, 2022

MRPTS implemented 2008
Beaver (*Castor canadensis*) recolonization first noted 2013




45°F
03/21/2023
09:10PM
CREW004


50°F
03/16/2023
06:38AM
CREW004


MR-Weir 1998


MR-Weir 2013


Beaver “maintenance” of MR-Weir

River otter (*Lontra canadensis*) recolonization first noted 2022

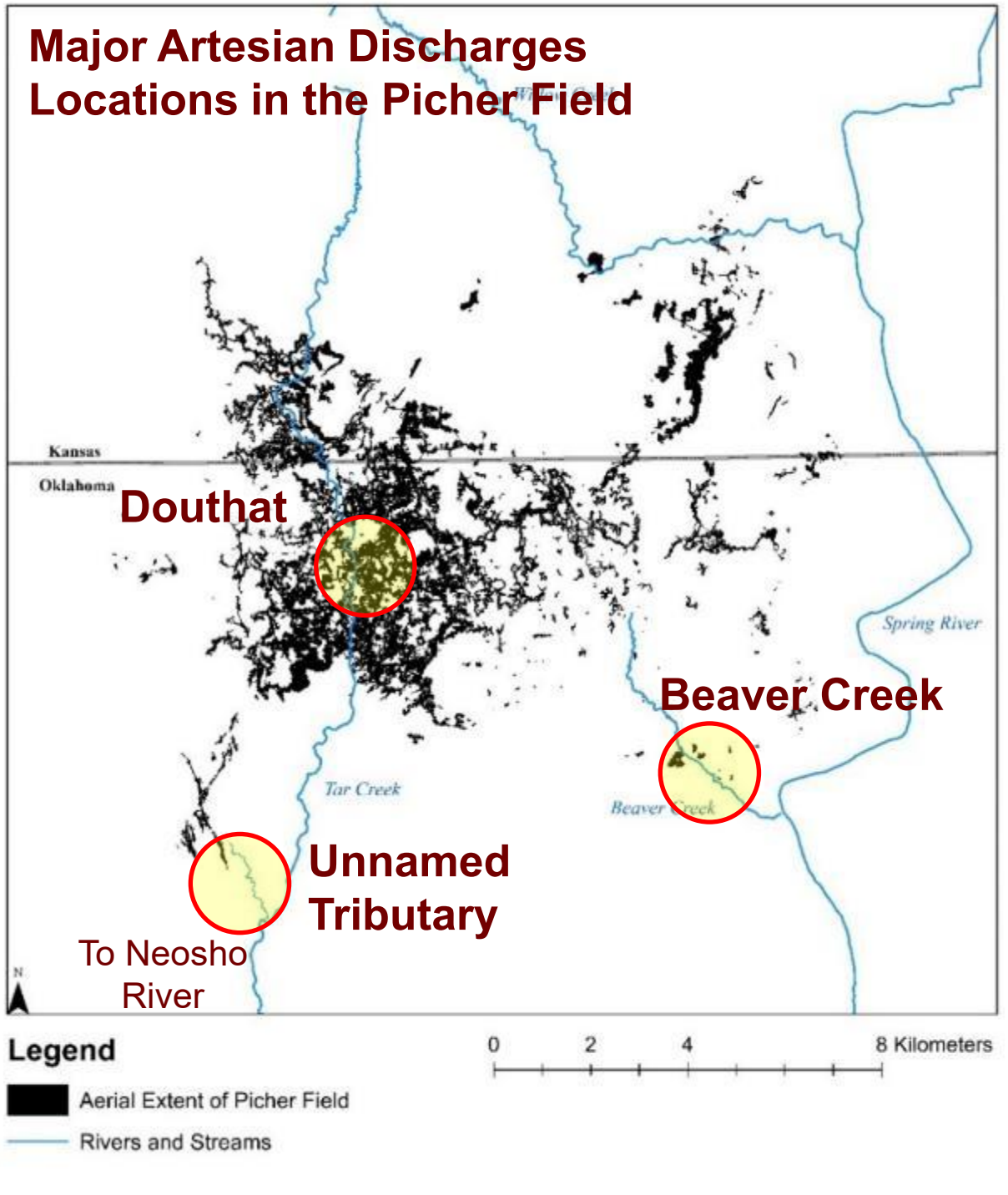

65°F
03/19/2023
09:41AM
CREW004


Pre-PTS
Post-PTS
Irreversibly Damaged?

What comes next?

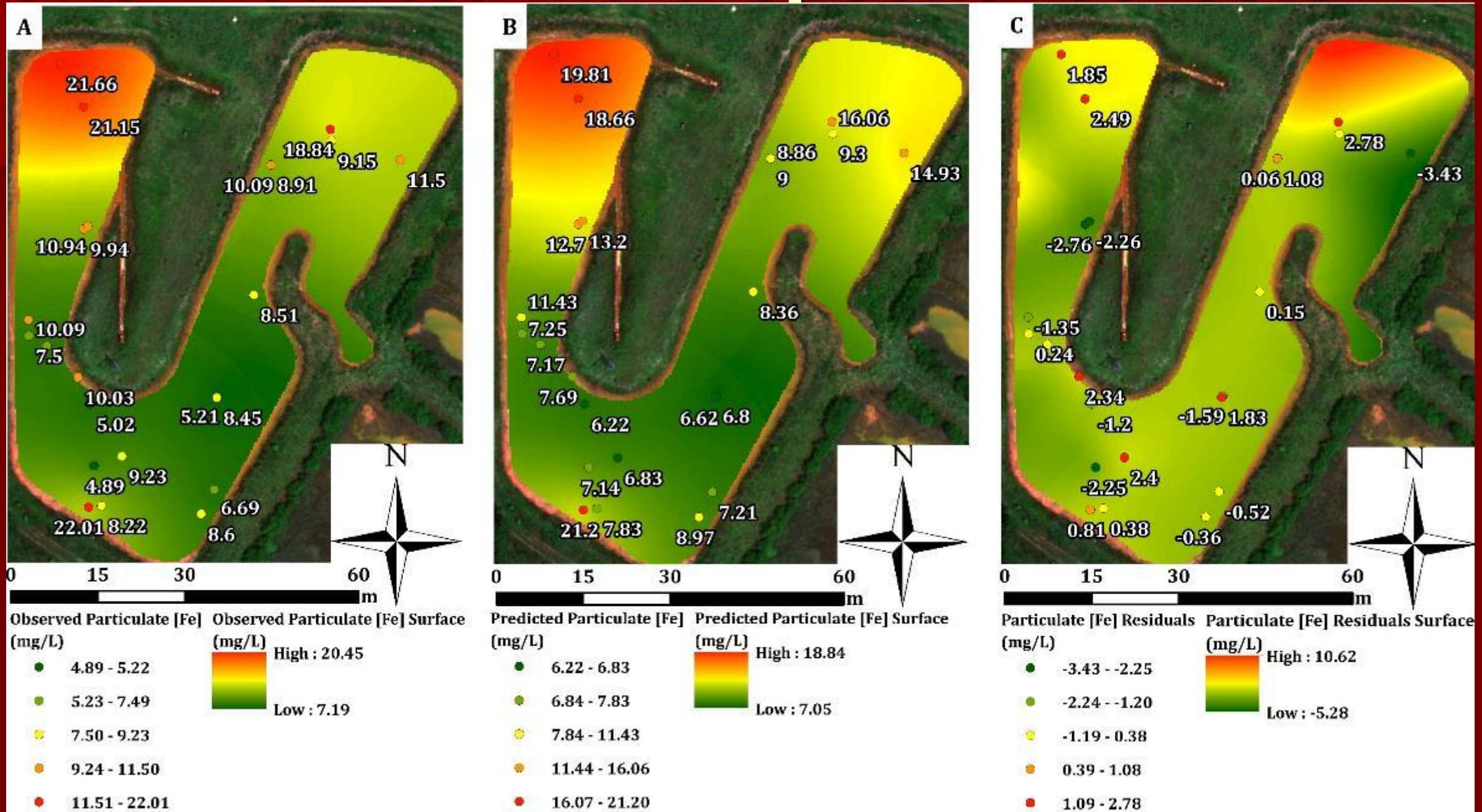
CREW
Center for Restoration of Ecosystems and Watersheds
The University of Oklahoma

- Unnamed Tributary
  - Two passive treatment systems
  - MRPTS: 16 years (November 2024)
  - SECPTS: 8 years (February 2025)
- Beaver Creek
  - Culturally important
  - Lesser concentrations; seasonal flows
  - Conceptual designs completed
- Douthat
  - Lesser concentrations
  - Seasonal – but much larger – flows
  - Conceptual designs completed



Novel environmental monitoring techniques

sUAS-mounted multi-spectral sensors

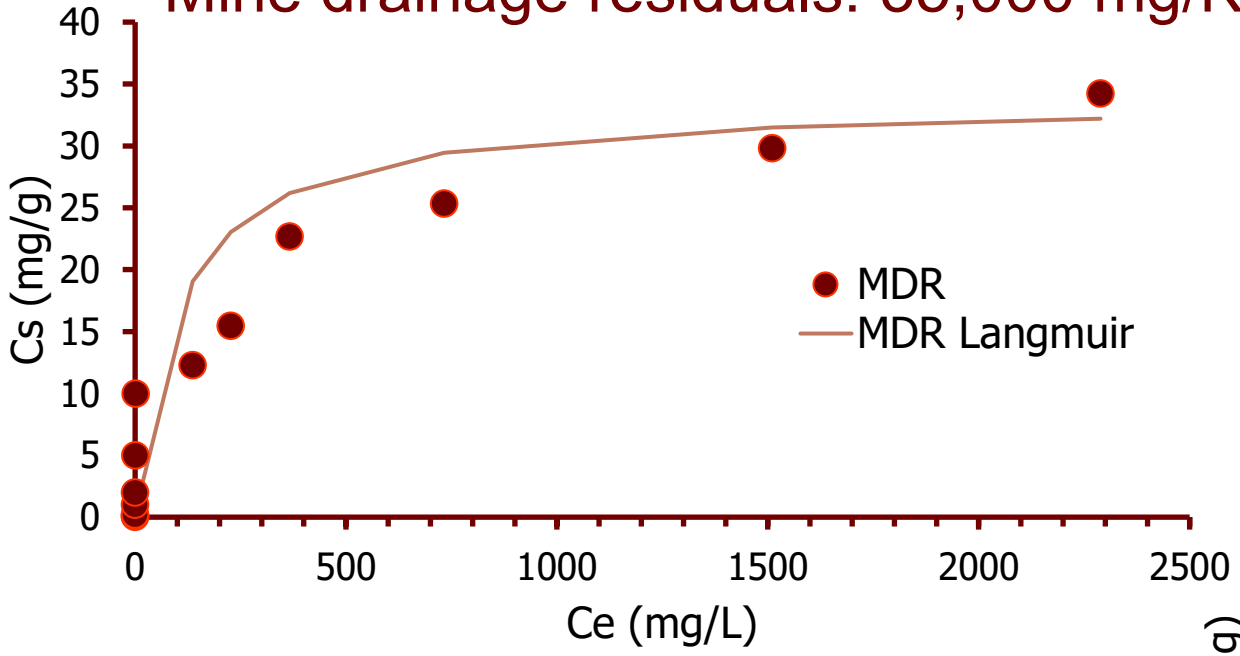


Resource Recovery

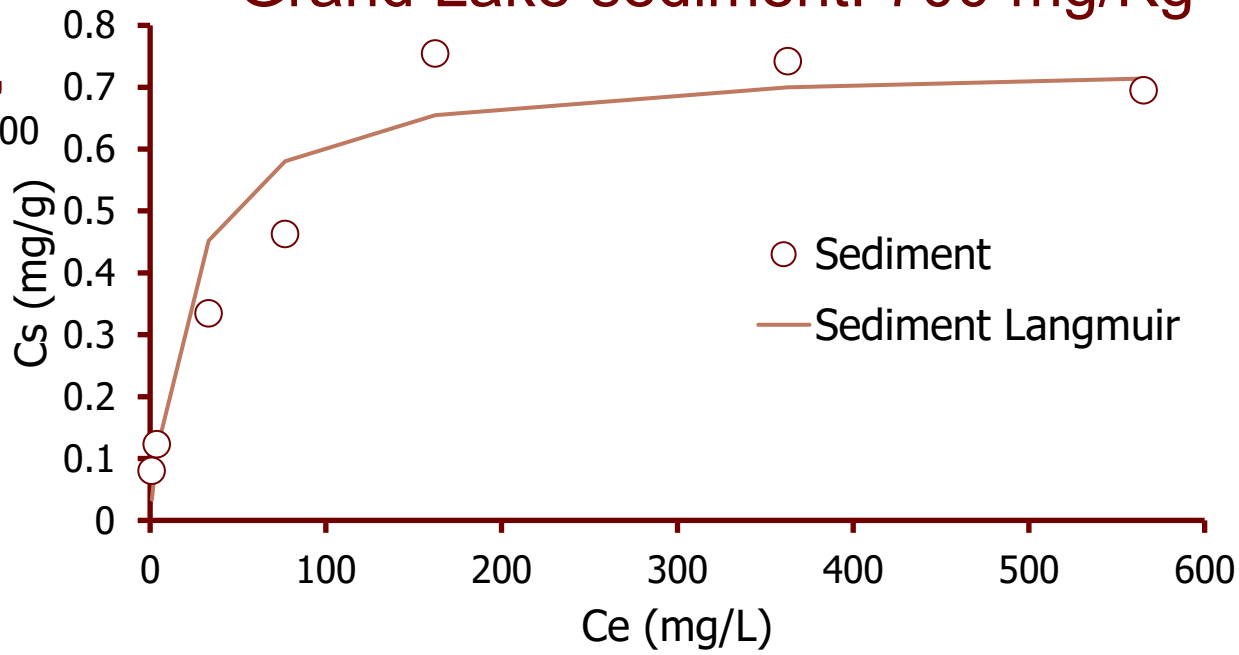
- Systems designed for metal accumulation as oxides or sulfides
- Process unit design lifetimes 20-25 years
- Potential beneficial reuse of accumulated solids?

Langmuir Phosphorus Sorption Isotherms

Mine drainage residuals: 35,000 mg/Kg



Grand Lake sediment: 700 mg/Kg



Substantial potential as P-sorption material

4. Conclusions

Conclusions

- Properly designed and sized passive treatment systems are demonstrated natural infrastructure solutions that improve mine water quality
- Improved water quality has direct influences on ecological metrics in stream and riparian areas
- Widespread applicability requires revisiting and revising administrative and regulatory constraints

2000 USEPA Five-Year Review Statement

- *"…the massive costs associated with any engineering remedy for surface water contamination in the Tar Creek Basin are still prohibitively high, and expenditures to meet those costs would drain the (Super)Fund. In short, there is no reason to revisit the fund-balancing waiver that was made in the 1984 OU1 ROD"*

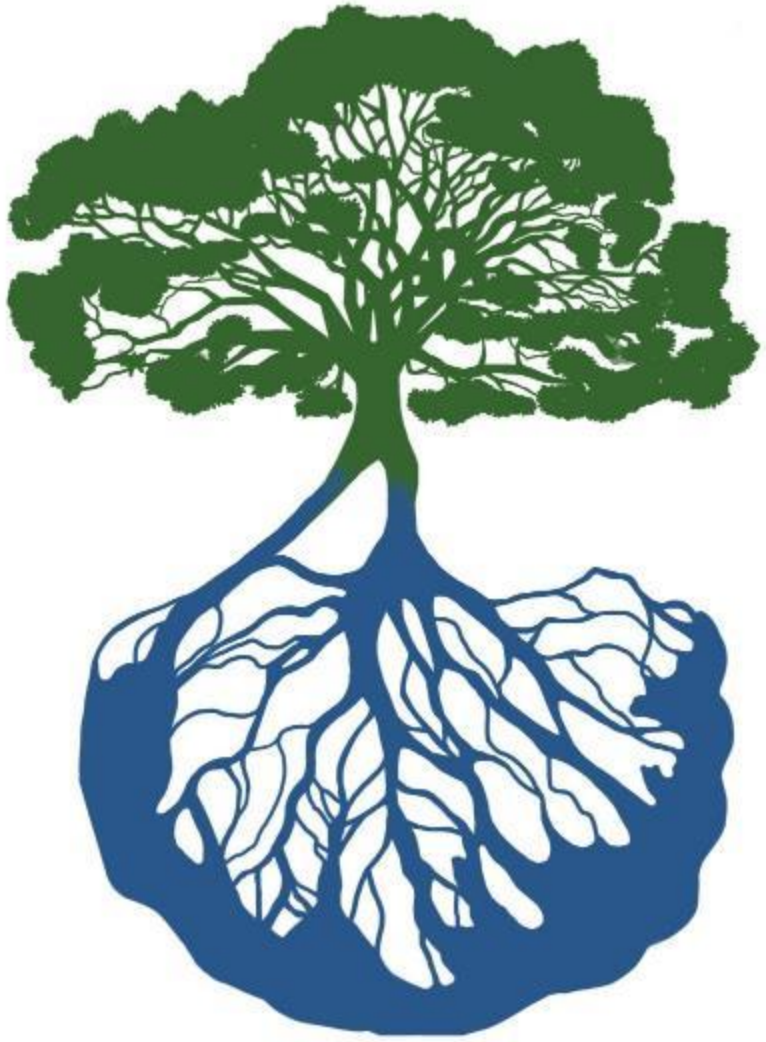
2015 USEPA Five-Year Review Statement

- *"…Treating mine water discharge via passive treatment appears to be economically feasible… the fund balancing applicable or relevant and appropriate requirements waiver… may no longer be valid and should be reevaluated…"*

2020 USEPA Five-Year Review Statement

- *EPA and its remedial action partners are considering opportunities to accelerate cleanup. Such opportunities may include , for example, considering the expansion of passive treatment wetlands to treat mine discharge water."*

Working together, nothing is irreversible.



NETWORK FOR ENGINEERING WITH NATURE

https://n-ewn.org/

CREW
Center for Restoration of Ecosystems and Watersheds
The University of Oklahoma

Thank you!

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