PILOT-SCALE CONSTRUCTED WETLAND TREATMENT SYSTEM PERFORMANCE AT A FORMER URANIUM MINE

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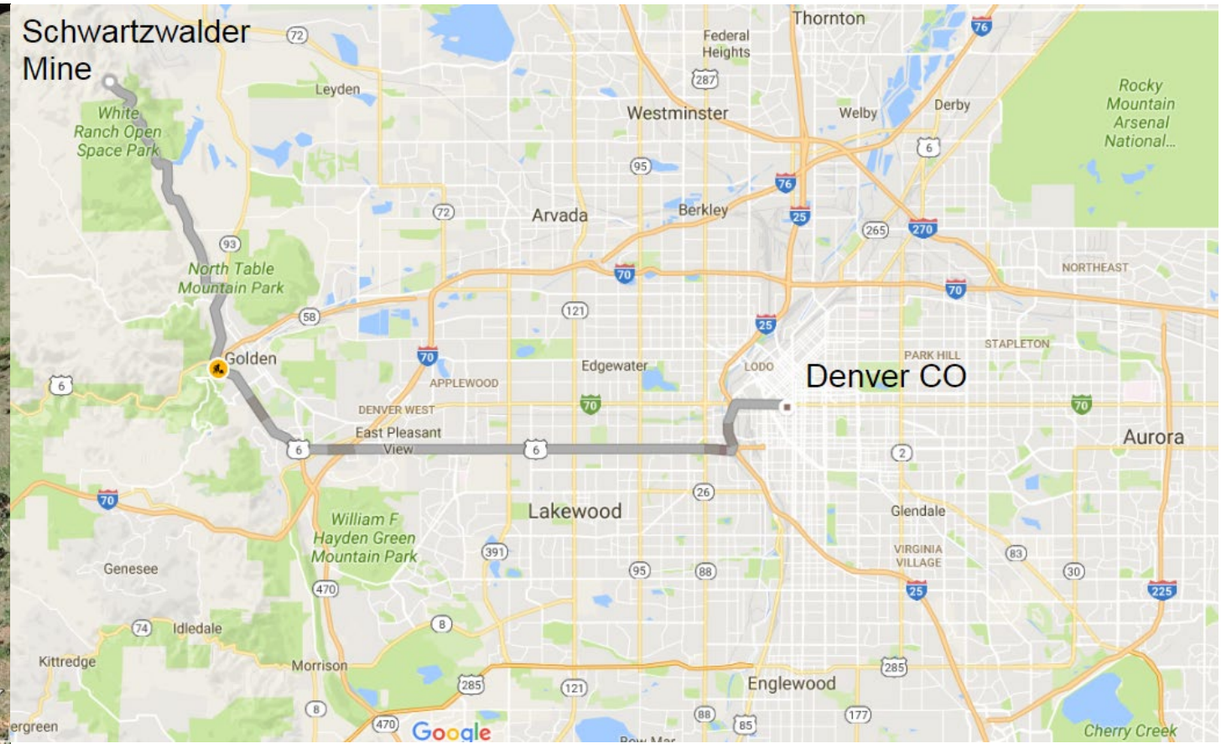
SCHWARTZWALDER MINE

~580 acre site, ~30 acres disturbance

Deep underground uranium mine



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A BRIEF HISTORY

Figure 9. Schwartzwalder Mine, 1993. (Photograph courtesy of Jim Paschis)

Enhanced mineralization and erosion expose uranium ore at the surface

1953
Schwartzwalder Mine opens

1998
Dewatering of sub-19 Level Ceases

2018
CLL Acquires Schwartzwalder Mine; Final Reclamation Begins

Mine Operations

Pre-discovery | 1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s

X Avg Crustal Abundance

U	70,700
Mo	4,800
Sb	2,200
W	1,150
Pb	600
Tl	400

1966
Property sold to Cotter Corporation

2000
Mining Ceases and Upper Mine Begins to Flood

1949
Ore deposit discovered by Fred Schwartzwalder by surface sampling

2007
Mine Pool Elevation Reaches Creek Level

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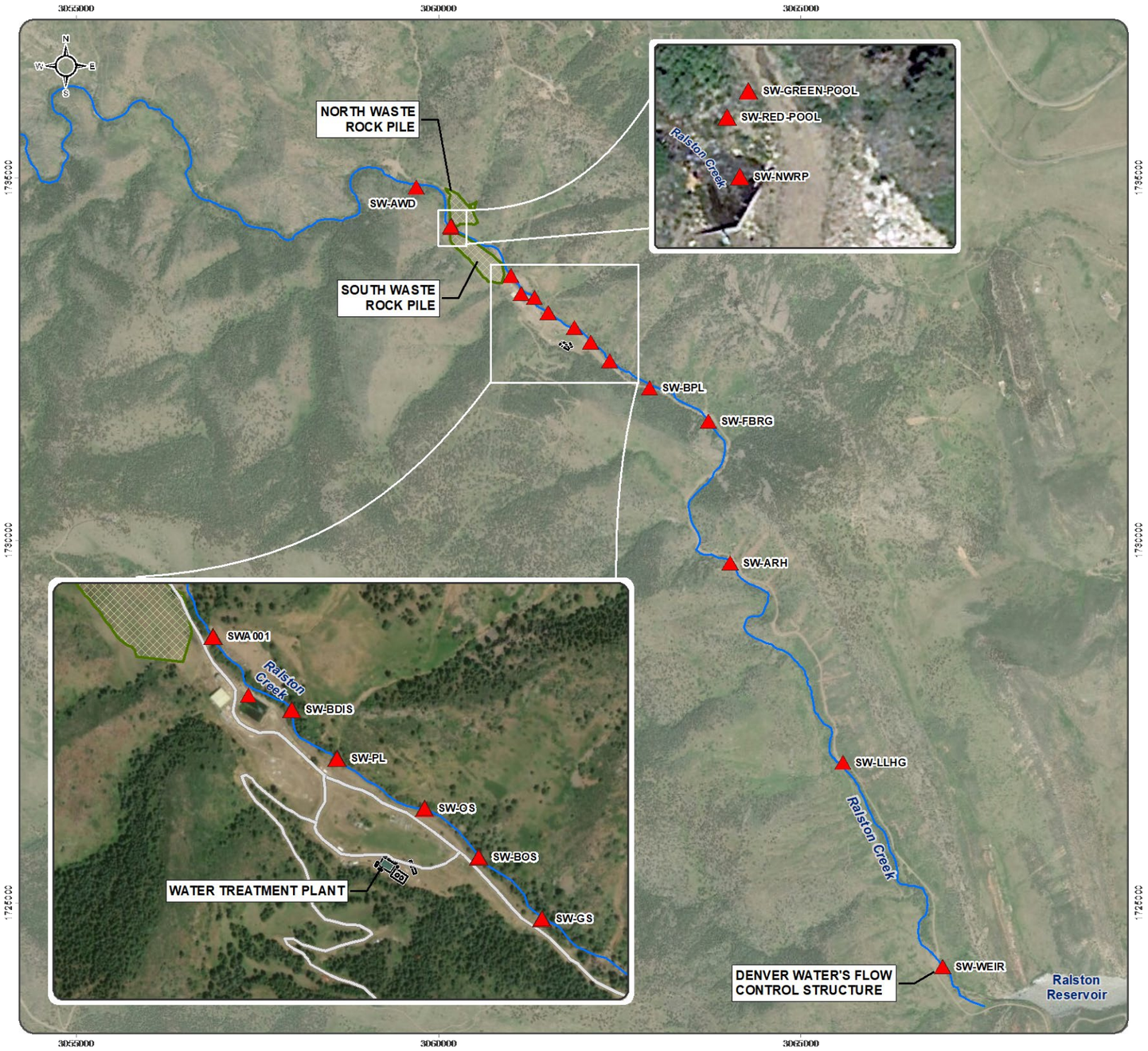
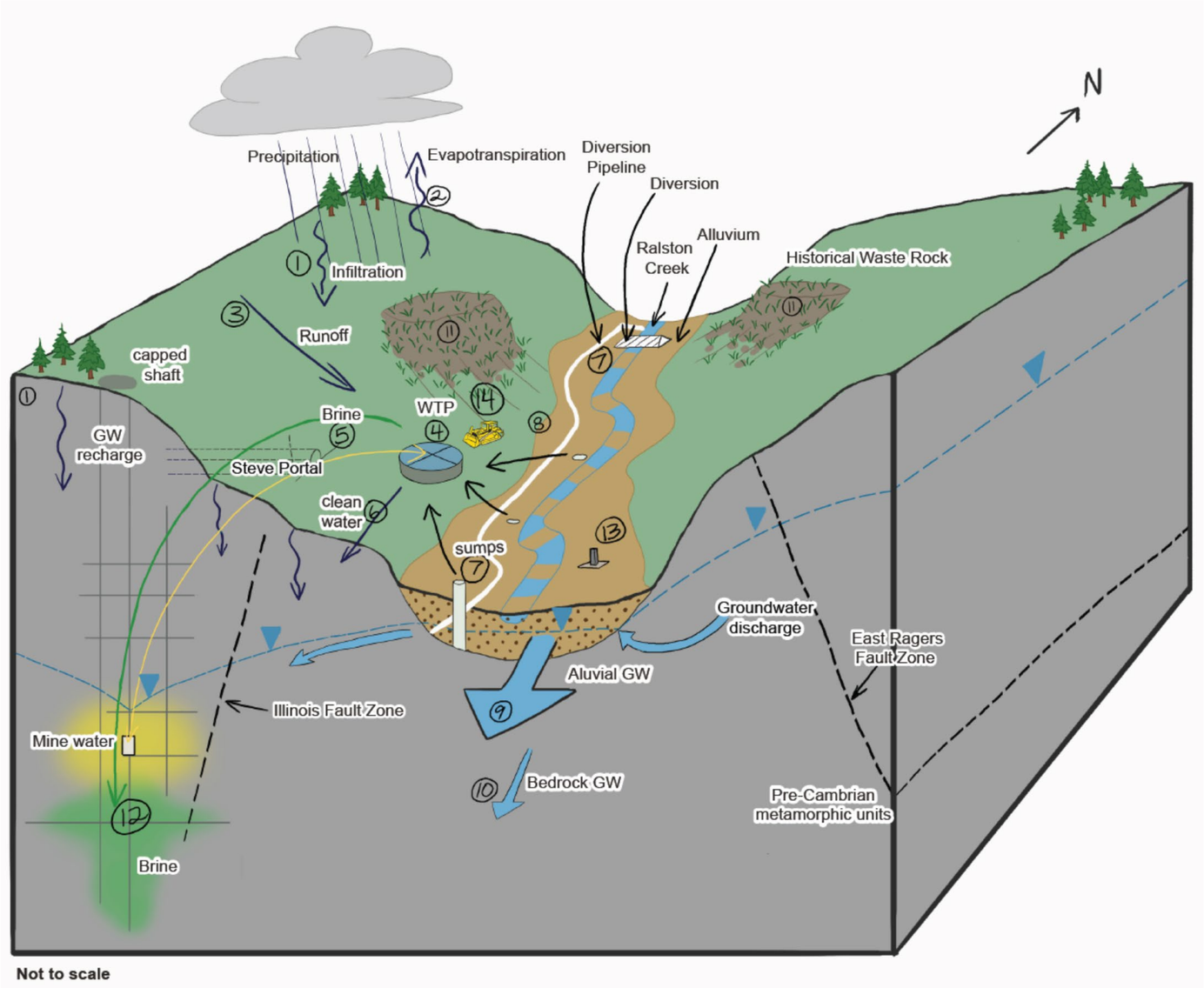
SCHWARTZWALDER MINE IS ADJACENT TO RALSTON CREEK



The site is owned by Colorado Legacy Land which is managed by Legacy Land Stewardship, a Public Benefit Corporation. Colorado Legacy Land acquires environmentally-challenged properties for the purposes of environmental closure, redevelopment, and long-term environmental stewardship. Ensero Solutions is the Site operator.

CONCEPTUAL SITE MODEL: WATER TREATMENT



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WATER TREATMENT SOLUTIONS

Potential Technologies Appropriate to the Project Lifecycle Phase and Climate

SOLUTIONS

CHEMICAL REACTOR
- Lime Treatment
- Sulfide reagents
- Ferric iron sorption and coagulation
- Chlorination
- Oxidants

CONCENTRATION
- Reverse osmosis
- Nanofiltration
- Microfiltration
- Ion exchange
- Evaporation
- Solids management

BIOREACTOR
- Sulfate reducing
- Denitrifying
- Ammonia oxidation
- Membrane
- Activated sludge

IN SITU TREATMENT
- Pit lake
- Underground mine pool
- Groundwater plume remediation
- Tailings pond

NATURAL TREATMENT
- Constructed or natural wetlands
- Aquatic ecosystem
- Living covers
- Land application
- Natural attenuation

- Active treatment technologies are appropriate during operations and transition to closure
- Mine closure that does not require perpetual active treatment is an issue the mining industry has grappled with unsuccessfully
- Biological, in situ, and natural treatment systems have promise to reduce perpetual operating costs
- Reclamation design can complement/enable more passive water treatment technologies to be used during permanent closure

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Potential Technologies Appropriate to the Project Lifecycle Phase and Climate

SOLUTIONS

CHEMICAL REACTOR	CONCENTRATION	BIOREACTOR	IN SITU TREATMENT	NATURAL TREATMENT
• Lime Treatment	• **Reverse osmosis**	• **Sulfate reducing**	• Pit lake	• **Constructed or natural wetlands**
• Sulfide reagents	• Nanofiltration	• Denitrifying	• **U/g mine pool**	• Aquatic ecosystem
• Ferric iron sorption and coagulation	• Microfiltration	• Ammonia oxidation	• Groundwater plume remediation	• Living covers
• Chlorination	• **Ion exchange**	• Membrane	• Tailings pond	• Land application
• Oxidants	• Evaporation	• Activated sludge		• Natural attenuation
	• Solids management			

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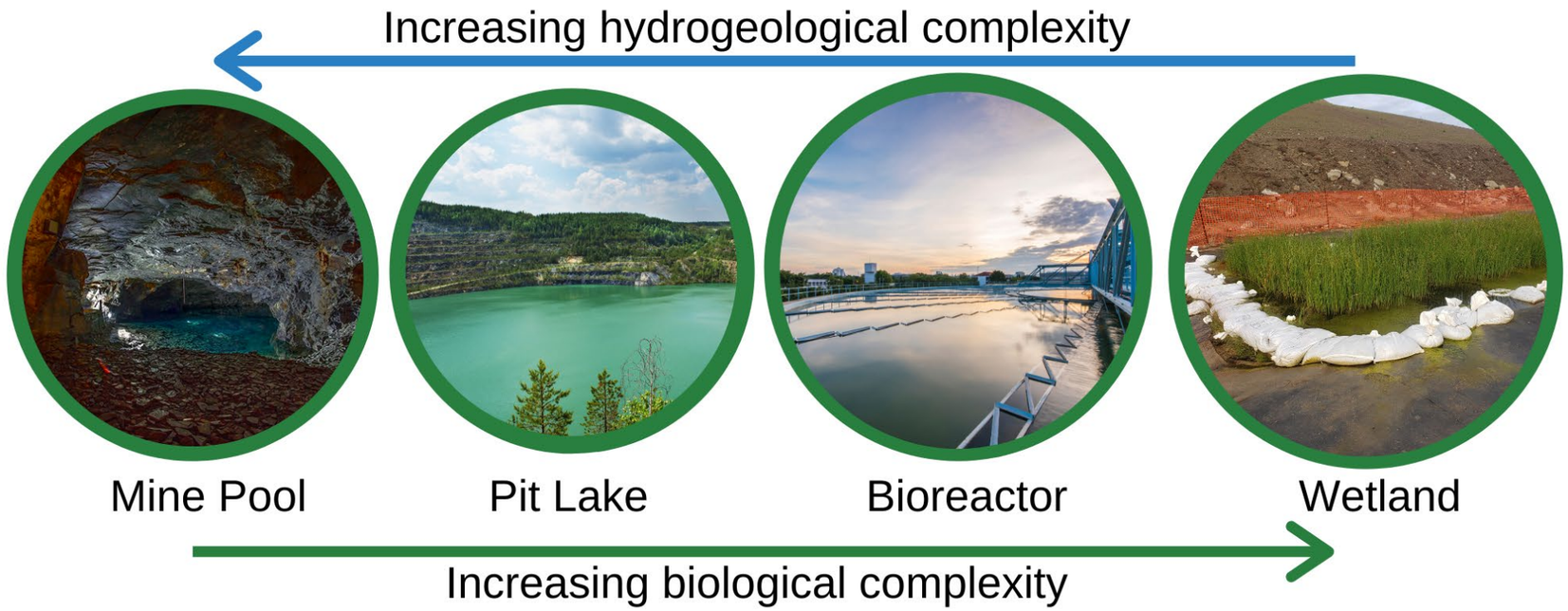
BACKGROUND
WHAT IS PASSIVE/SEMI-PASSIVE TREATMENT?

- Generally operationally passive (or can be operated remotely)
- Have minimal long-term maintenance requirements
- Examples are BCR and CWTS
- All water treatment systems require some degree of operational management and long-term maintenance



WHAT IS A CWTS AND HOW DOES IT WORK?

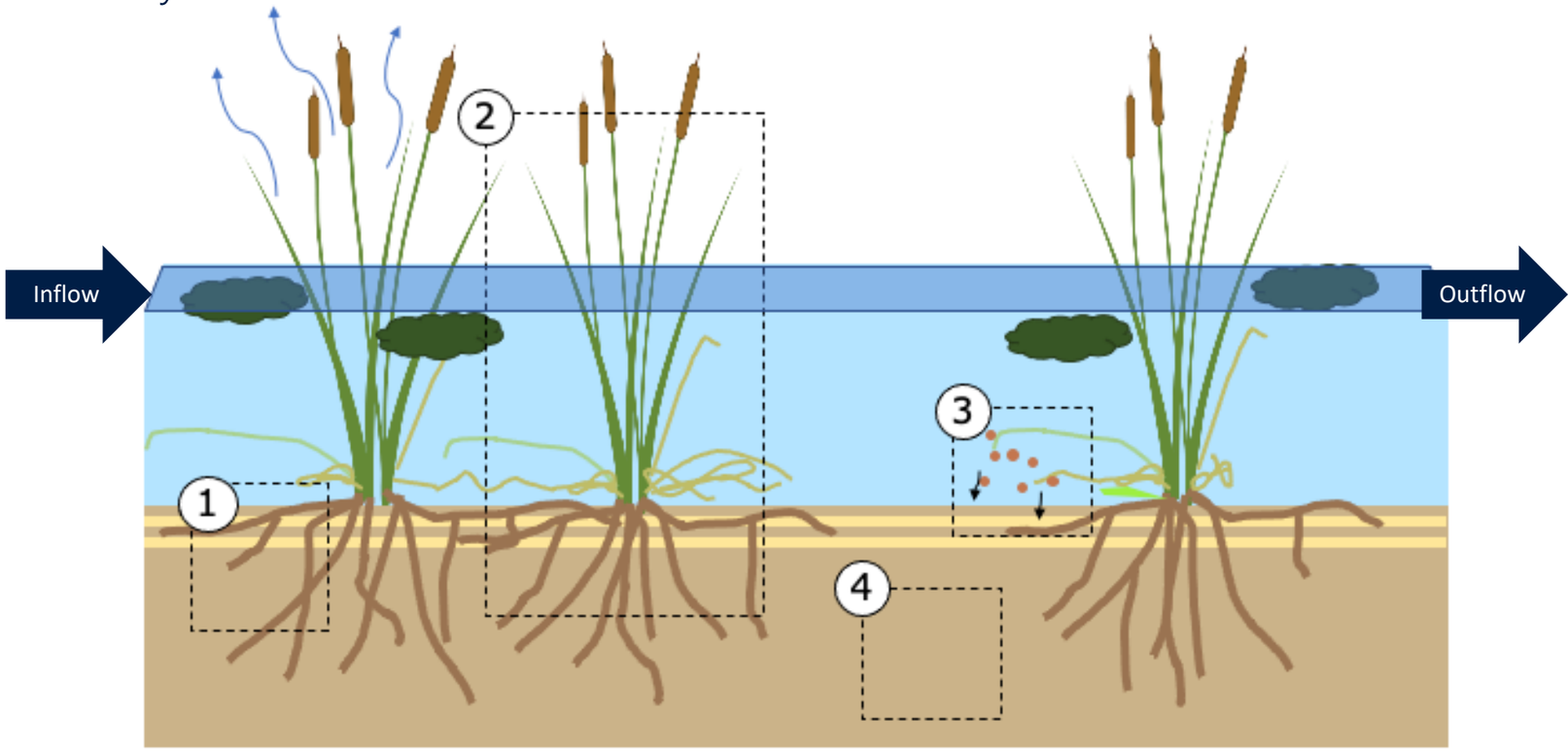
- *Constructed Wetland Treatment System*
- Largely passive treatment system, infrequent (annual) maintenance
- Individual cells are designed for treatment of water using monoculture (not designed for wildlife/habitat restoration)
- CWTS can be designed as anaerobic or aerobic systems to treat different constituents

1- Microbial Metal and Metalloid Treatment

2- Plants help with treatment (but not by uptake)

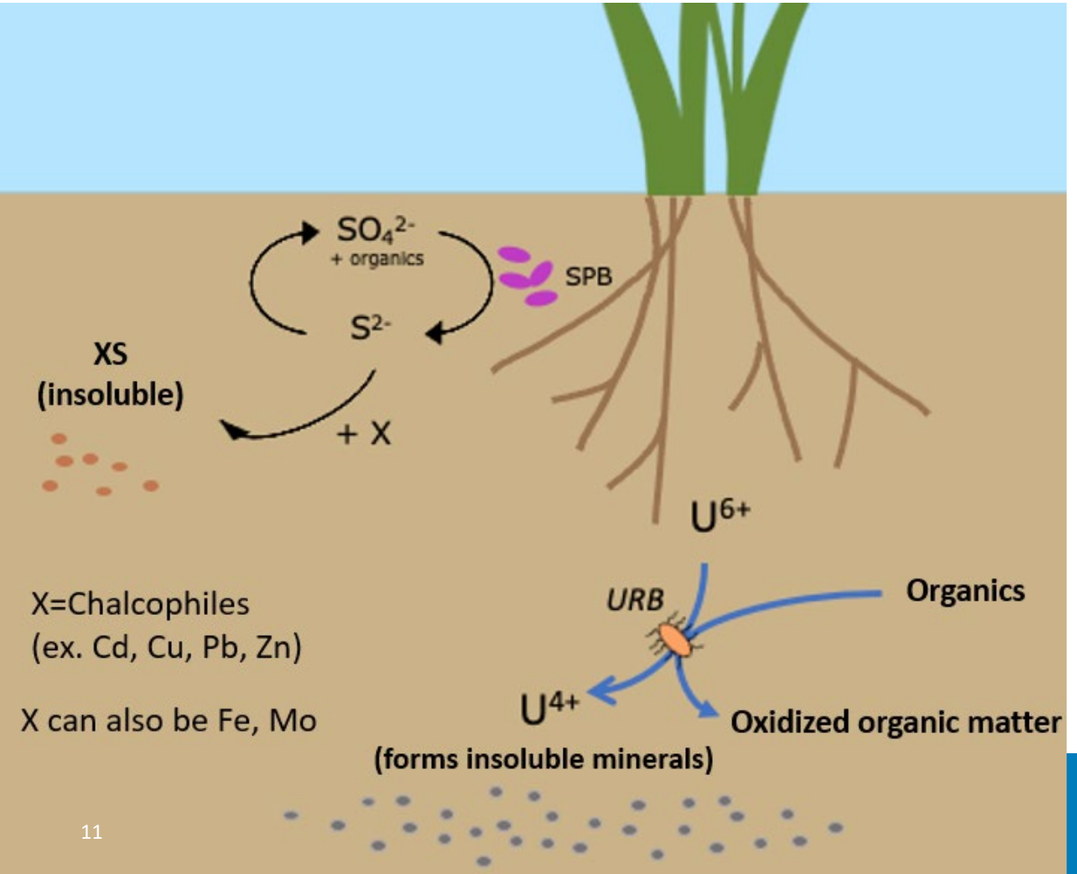
3- Accretion

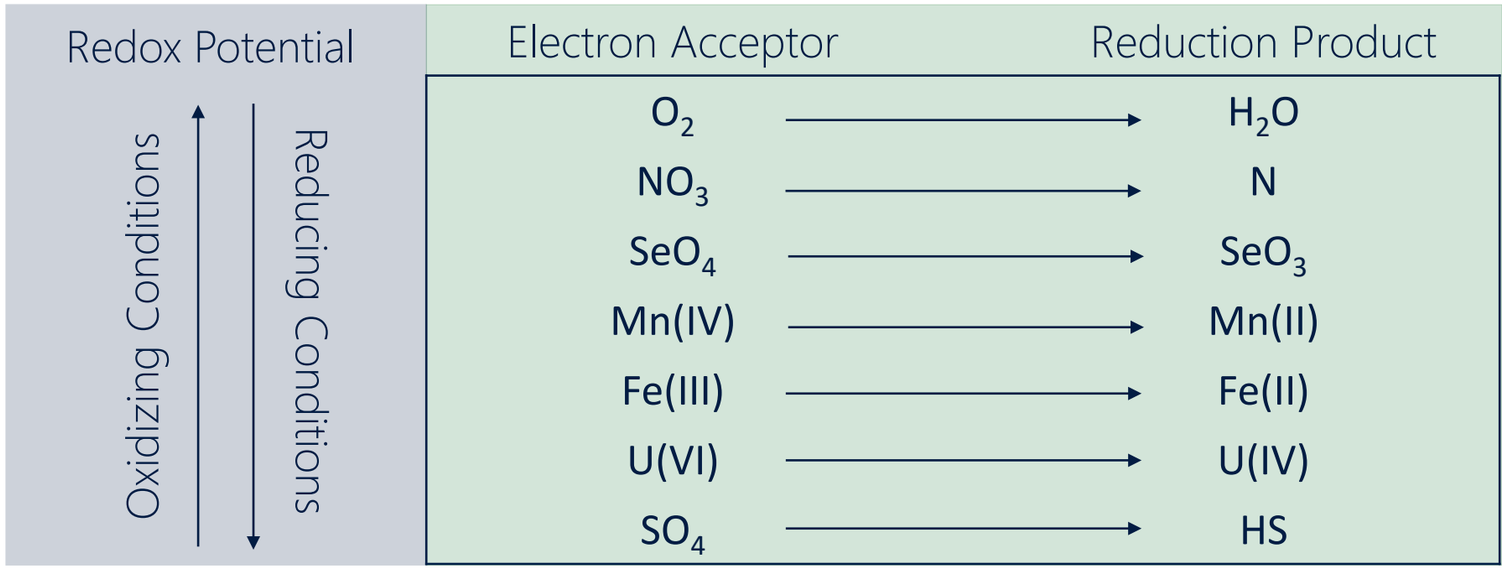
4- Substrate



BACKGROUND
HOW DOES A CWTS TREAT URANIUM?

- Anaerobic CWTS was selected for treatment of U
- Targeted treatment mechanism: Microbial mediated reduction of soluble U(VI) to insoluble U(IV)
- Targeted reducing conditions: Sulfate-reducing conditions





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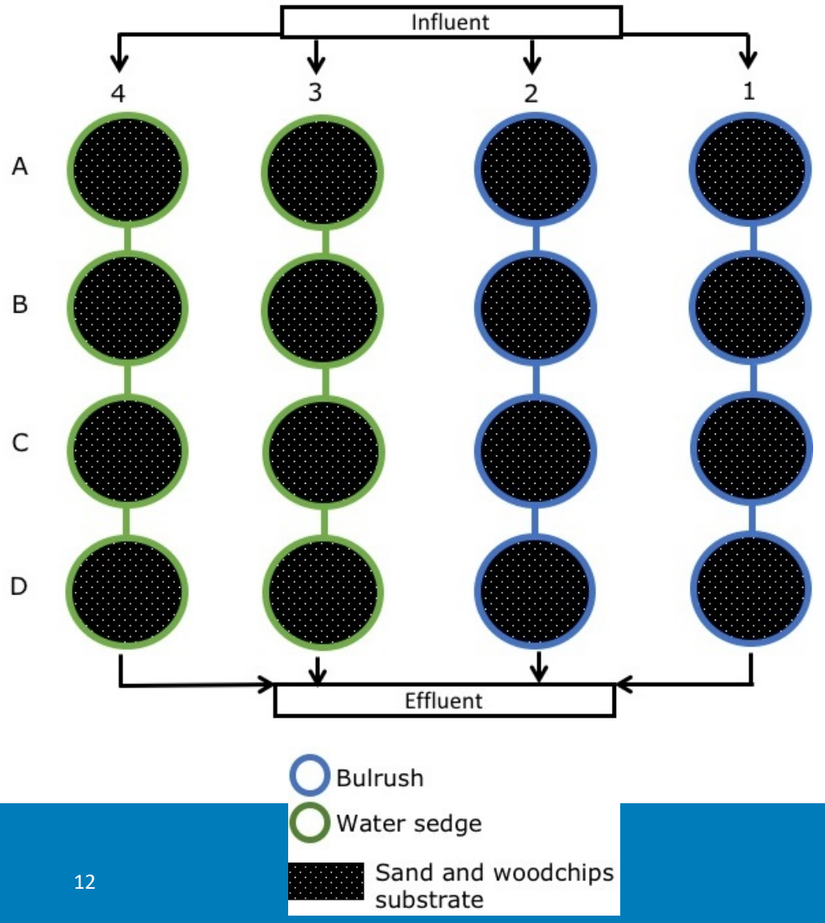
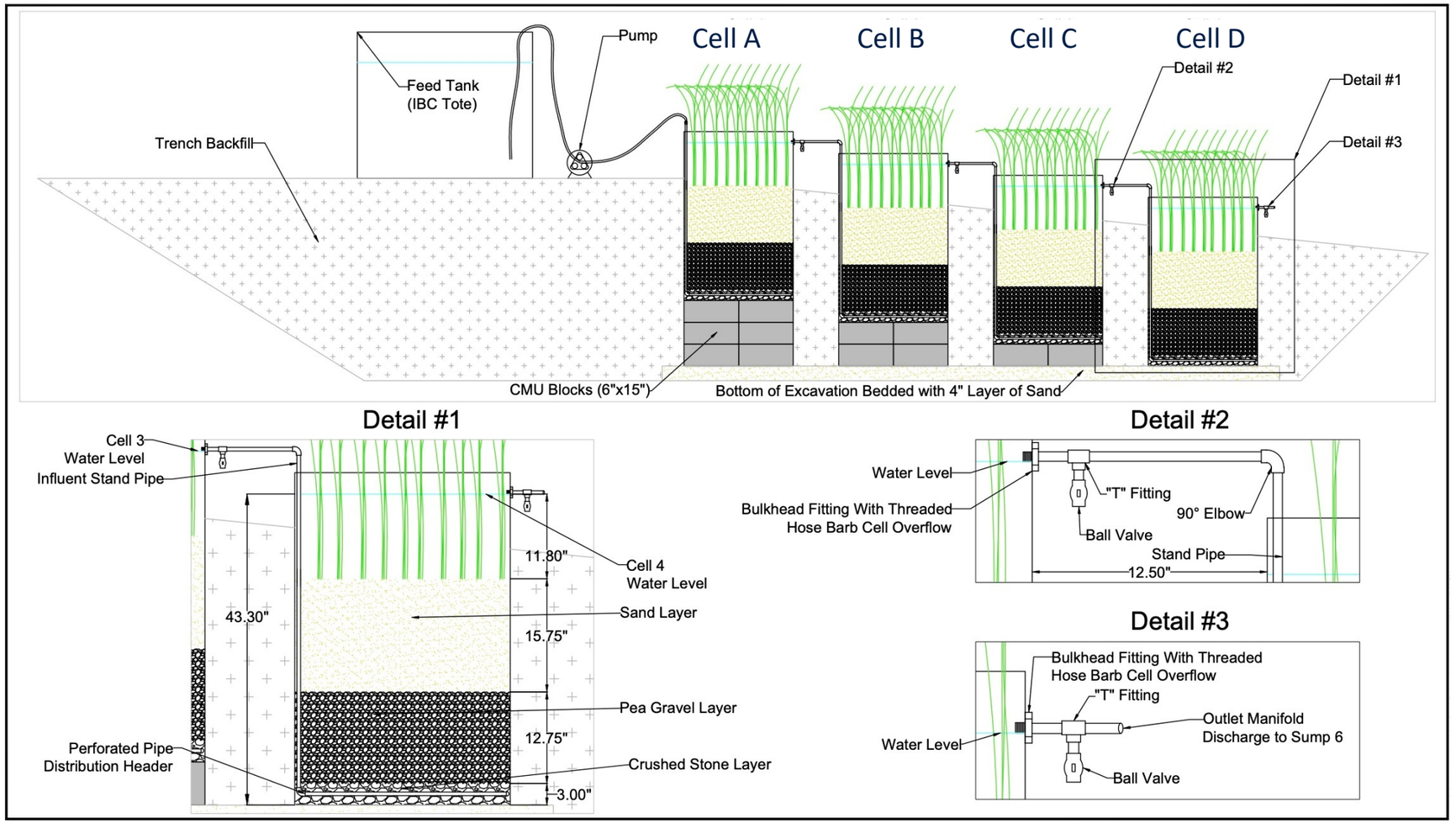
CWTS DESIGN
SET-UP AND TEST PARAMETERS

- Two plant types
- Vertical up flow configuration





CWTS DESIGN
CONSTRUCTION

- Built on-site outside the RO water treatment plant
- Water flow upward from the distribution header, the gravel, peagravel, then sand, and up the water column
- Buried in the ground to help plant survival over winter

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CWTS COMMISSIONING
CWTS MATURATION AND DEVELOPMENT

- Takes about 1 year to commission
- Commissioning Criteria
  - Achieving reducing conditions
  - Adequate plant growth
- Commissioning Activities
  - Increasing mine pool water in influent
  - Increasing water level with plant growth
  - Adding straw

COMMISSIONING PERIOD CONCEPTUAL TARGETS			
Water		**Soil**	**Vegetation**
DO	**ORP**	**Redox**	**Density**
< 2 mg/L	< 50 mV	< -100 mV	50% increase

End of commissioning (based on establishing reducing conditions)

Bulrush cell 2B overtime

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CWTS PROGRESSION INTO OPERATIONS
CWTS MATURATION AND DEVELOPMENT

- Bulrush plants established faster in 2019
- Water sedge showed some plant die-off in 2020
- Sulfate-reducing conditions confirmed
  - Commissioning criteria met
  - Fe and Mn made soluble
  - Sulfide production

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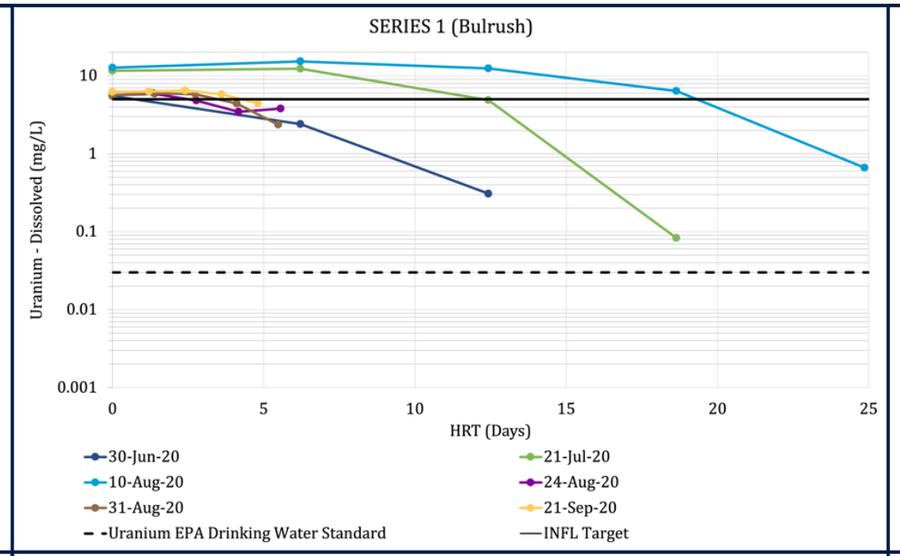
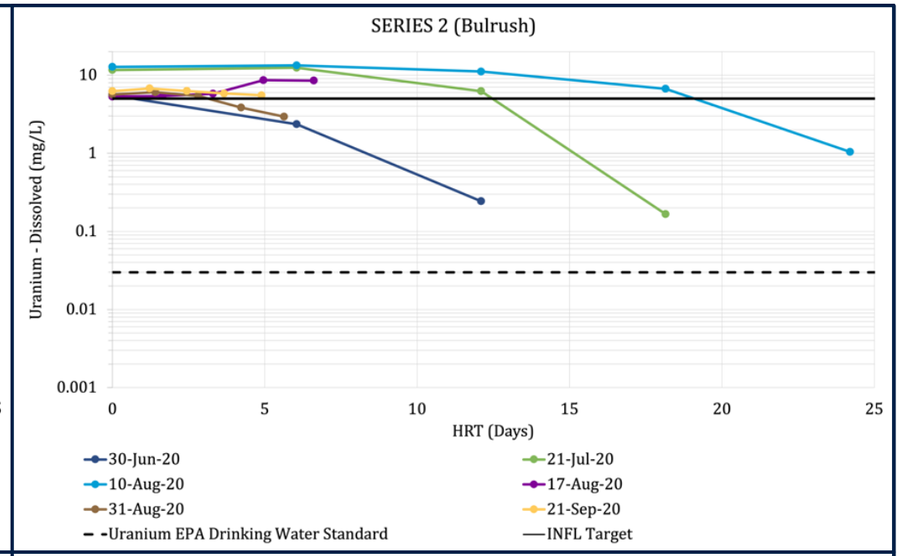
URANIUM TREATMENT

Bulrush

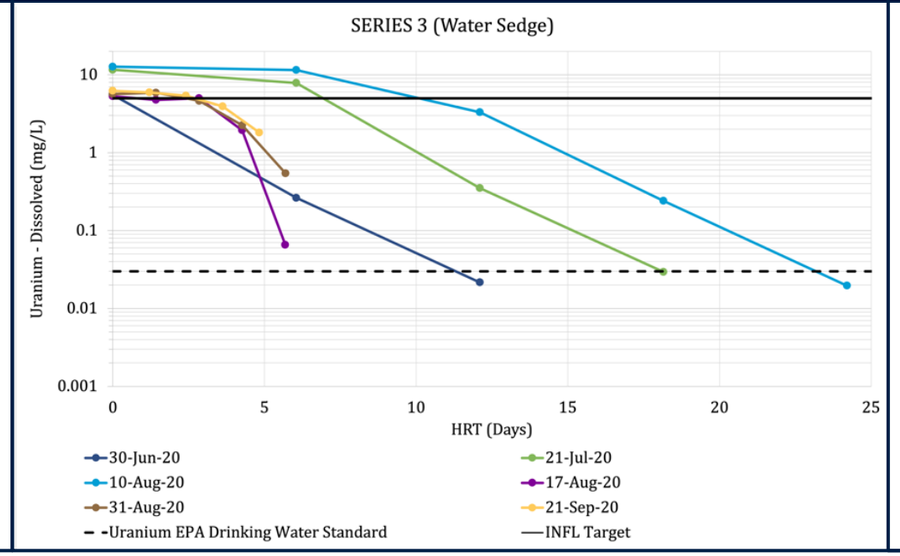


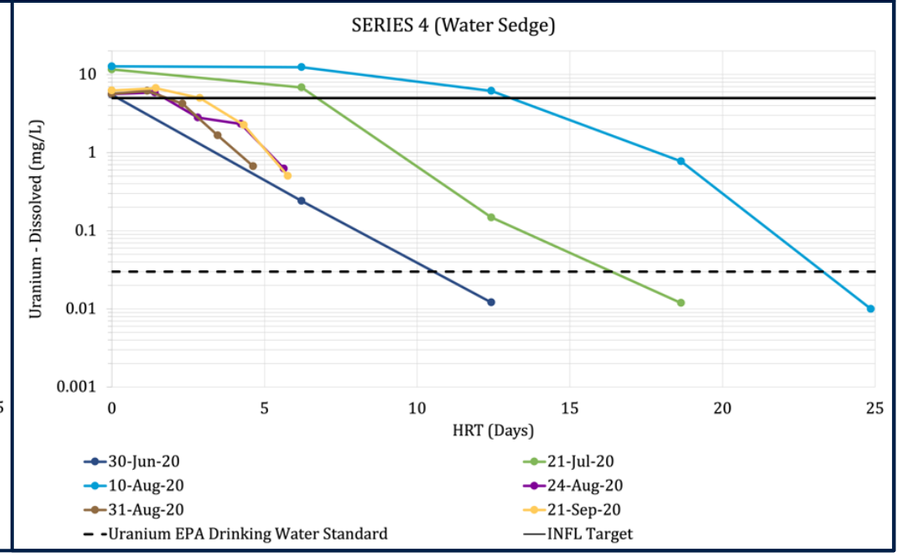


~30-45% removal at 5-day HRT

~95% removal at 25-day HRT

Water Sedge





~80-90% removal at 5-day HRT

~>99% removal at 25-day HRT

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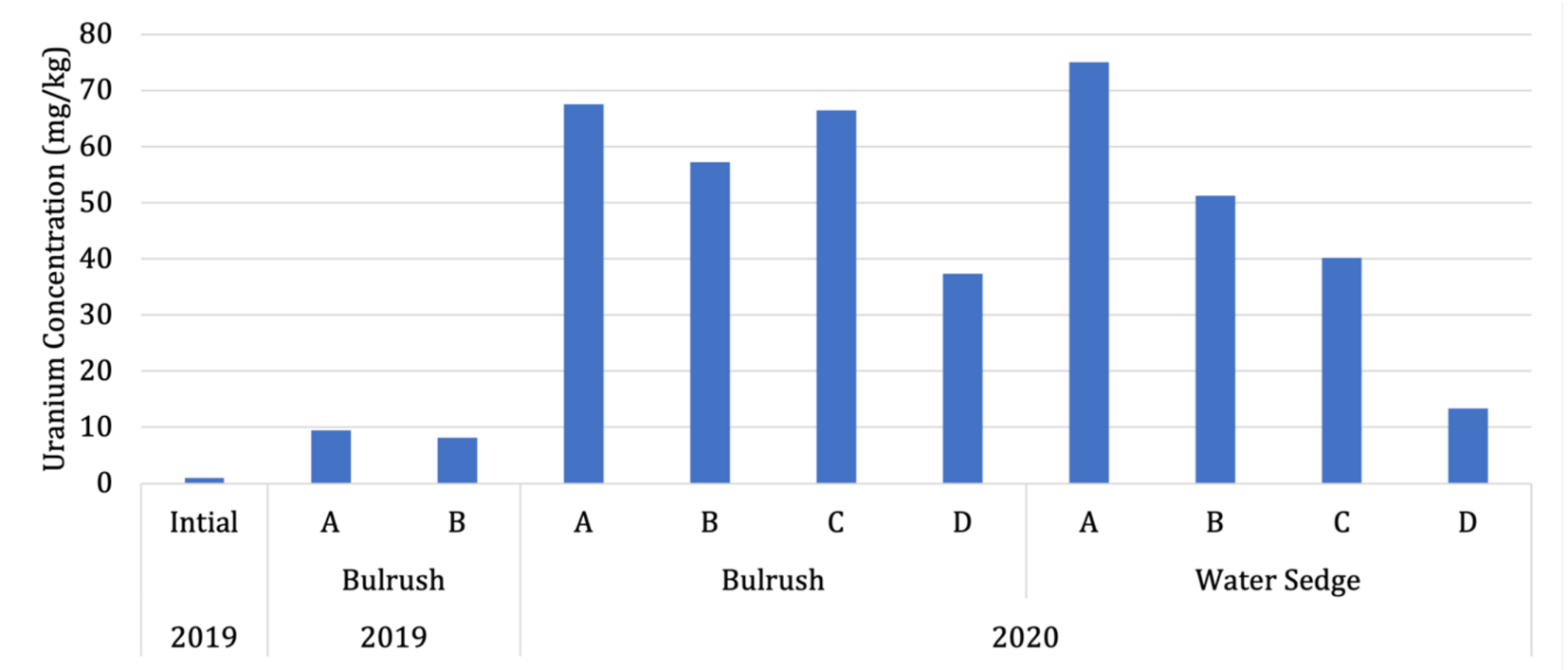
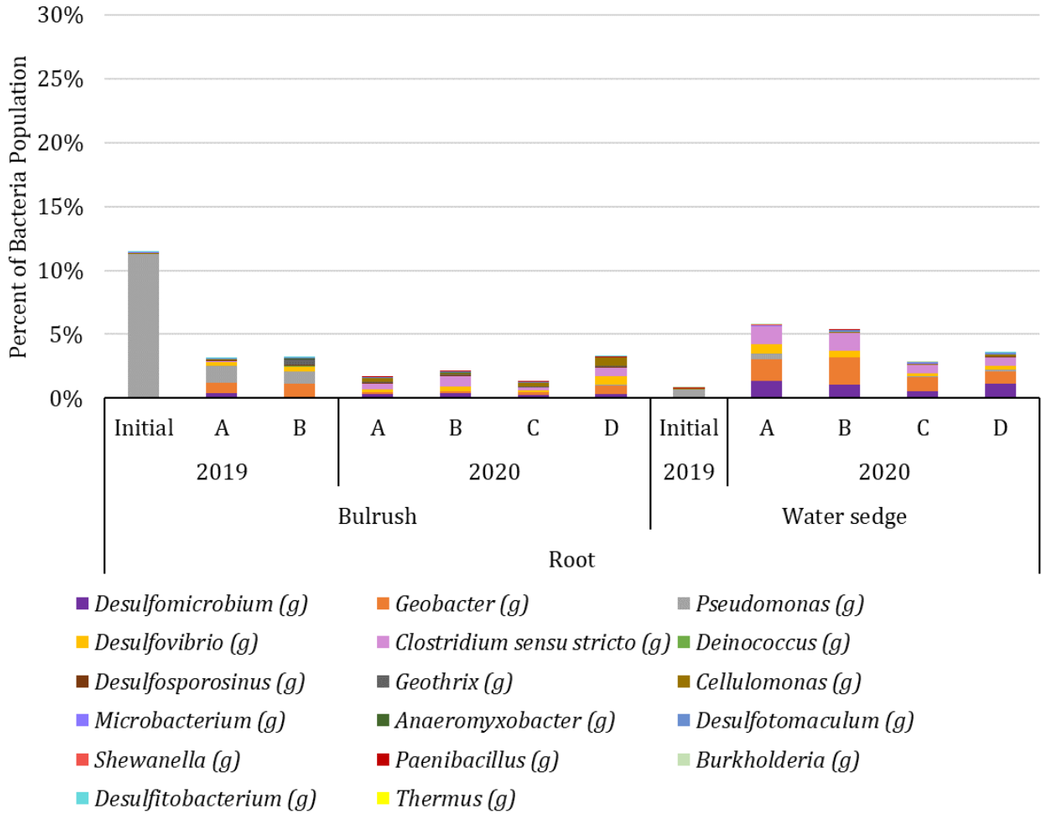
WHERE IS THE URANIUM BEING SEQUESTERED?

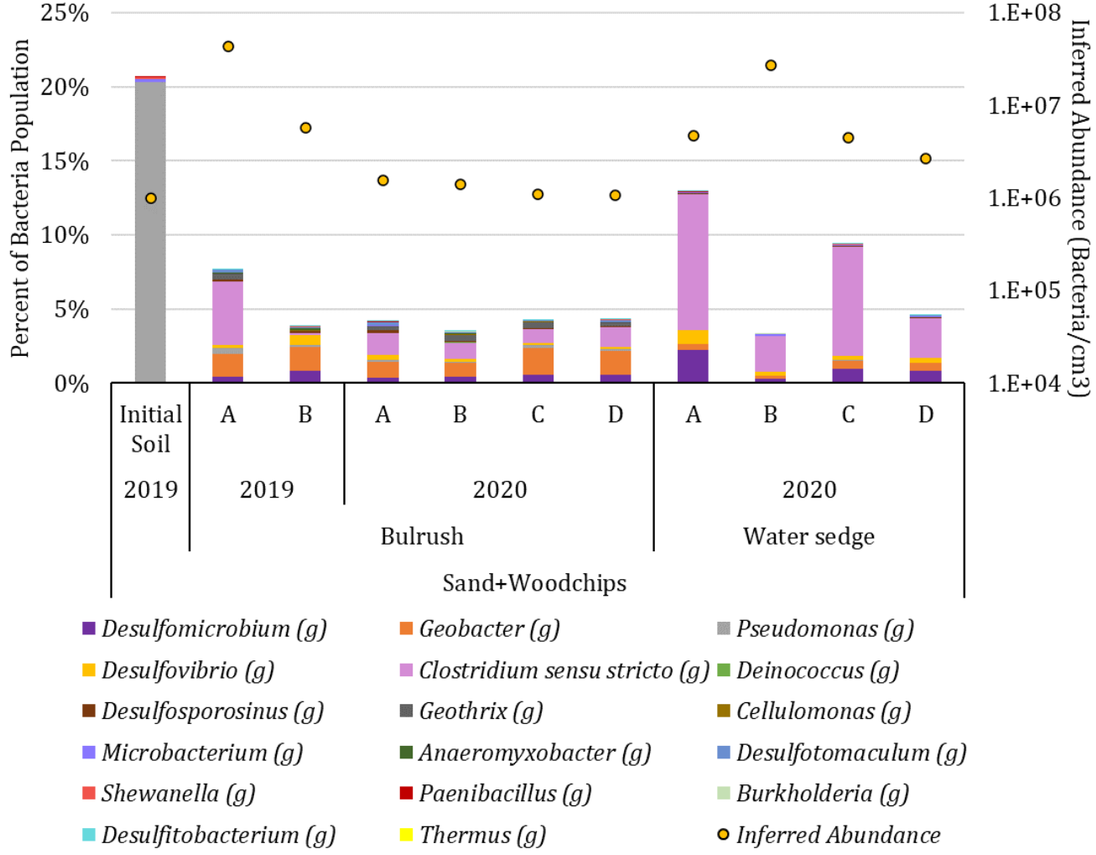
- Concentrations of U increase in the substrate overtime
  - The majority of U is loaded into the substrate/root zone/other components
    - Through microbial reduction (intended mechanism); and
    - Sorption to the substrate (finite, not targeted treatment mechanism)
  - Comparably small amounts of U plant uptake



URANIUM-REDUCING BACTERIA (URB)

- Changes in the microbial distribution show how the CWTS matured over-time
  - Increase in URB diversity
  - URB types shift to microbes where uranium reduction is more common to the genus
  - SPBs established (increased in diversity, percentage, and inferred abundance)





KEY FINDINGS

- Pilot-scale testing provided proof-of-concept for a CWTS at the Schwartzwalder Mine
  - Considerable treatment of U
    - U and sulfate-reducing conditions were achieved
    - U treatment by microbial reduction and sorption
    - Vast majority of U transformed into solid substrate and not into plants
    - Water sedge treated to lower concentrations
- Sedge and bulrush feed a carbon source to microbes in the substrate to drive the treatment reactions
  - Fermenting bacteria like *Clostridium* transform organics from plants into simple organic acids and alcohols that feed uranium and sulfate reducing bacteria
  - SRB and URB produce the insoluble uranium minerals and the redox buffer (FeS) that create a stable treatment condition
  - CWTS outperformed the BCRs (99%+ removal vs. 95% removal)
- 1-year period expected to commission CWTS
- Preliminary sizing of CWTS indicates 1-2 acre system would treat all water that would flow through Schwartzwalder Mine

RECOMMENDATIONS AND NEXT STEPS

- Progress to demonstration-scale testing
  - Refine treatment rates, commissioning criteria
  - Test potential future design considerations
    - BCR upstream of the CWTS
    - Bulrush CWTS upstream of water sedge CWTS
    - Longer HRTs (should bulrush be selected)
    - Aerobic polishing downstream of CWTS to treat leachable Fe or Mn

ACKNOWLEDGEMENTS

- Colorado Legacy Land
- Ensero Solutions field staff and plant operators
- Kessler Reclamation

QUESTIONS???

Ensero Locations
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