Evaluation of the Rotating Cylinder Treatment System™ at Elizabeth Mine, Vermont

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Disclaimer

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Outline

- **Elizabeth Mine site history**
- Water treatment for ferrous iron
- RCTS™ system and comparison to conventional lime treatment
- RCTS™ at Elizabeth Mine
- Lessons learned
- Final remarks

Elizabeth Mine, VT

Six Mining Sites with Superfund Activities in New England

<u>4 National Priorities List Sites</u>

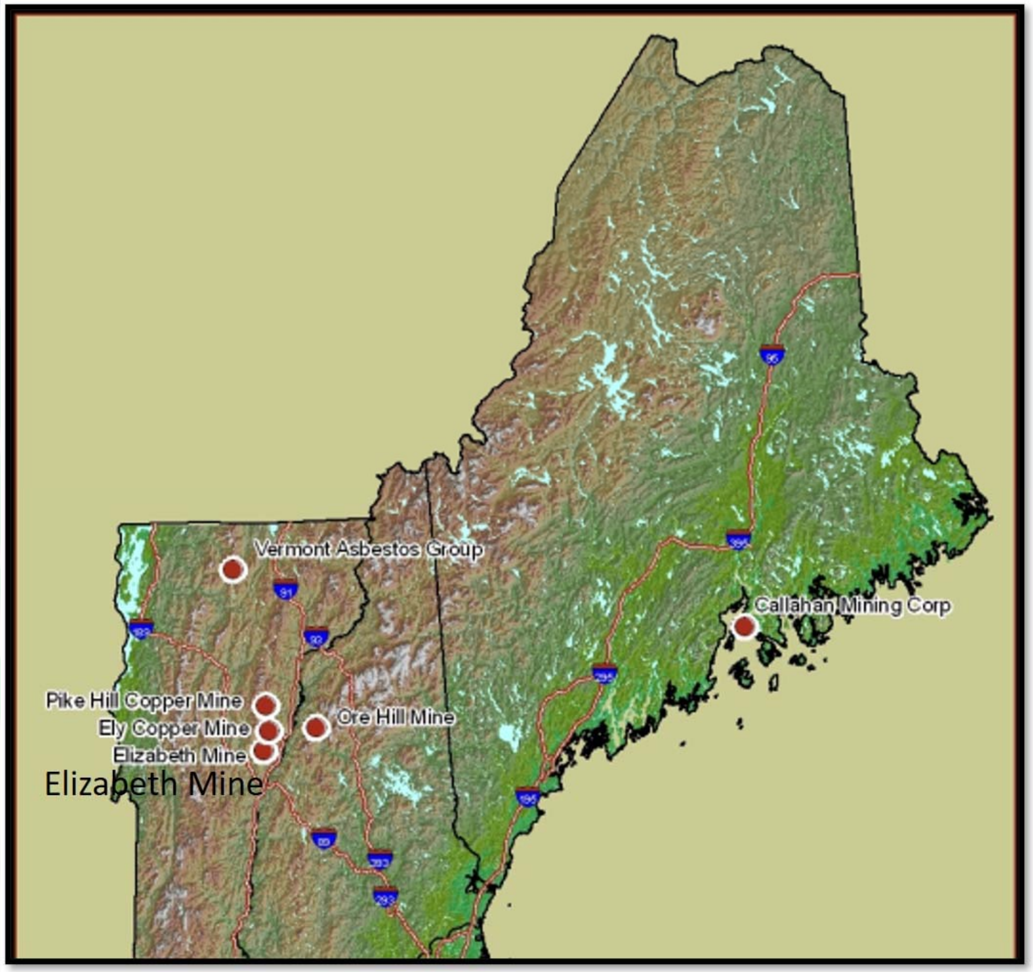
- **Elizabeth Mine (2001)**
- Ely Copper Mine (2001)
- Pike Hill Copper Mine (2004)
- Callahan Mining Corp (2002)

<u>1 EPA Removal Action</u>

- Vermont Asbestos Group (2007 – 2008)

<u>1 Forest Service Removal (NTCRA)</u>

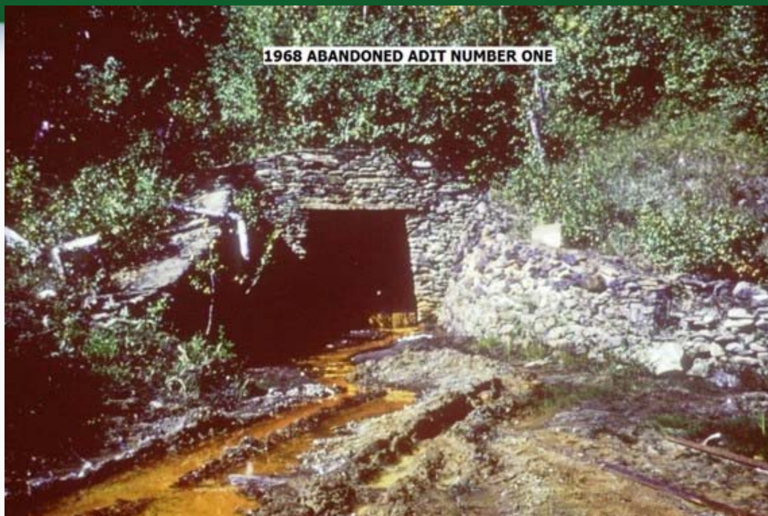
- Ore Hill Mine

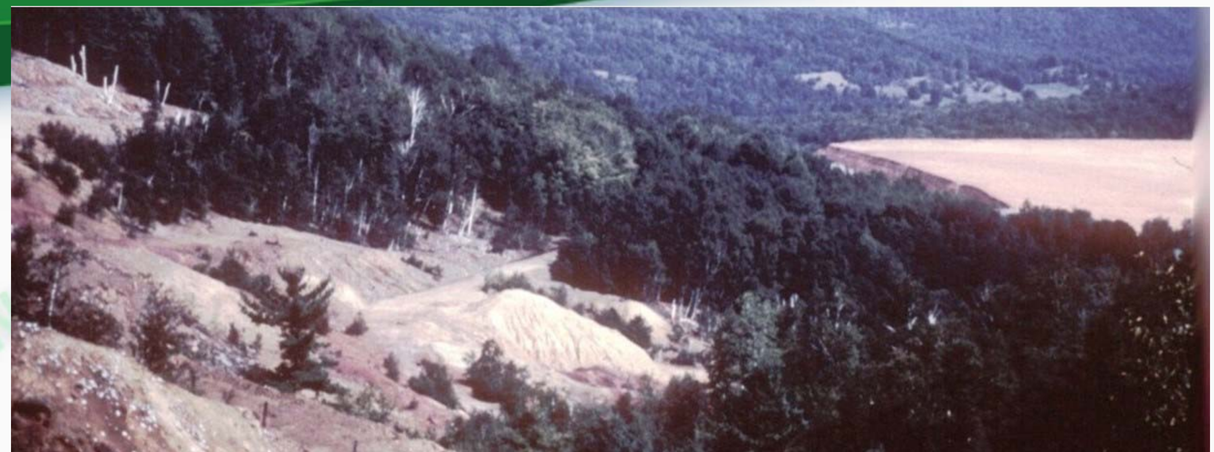


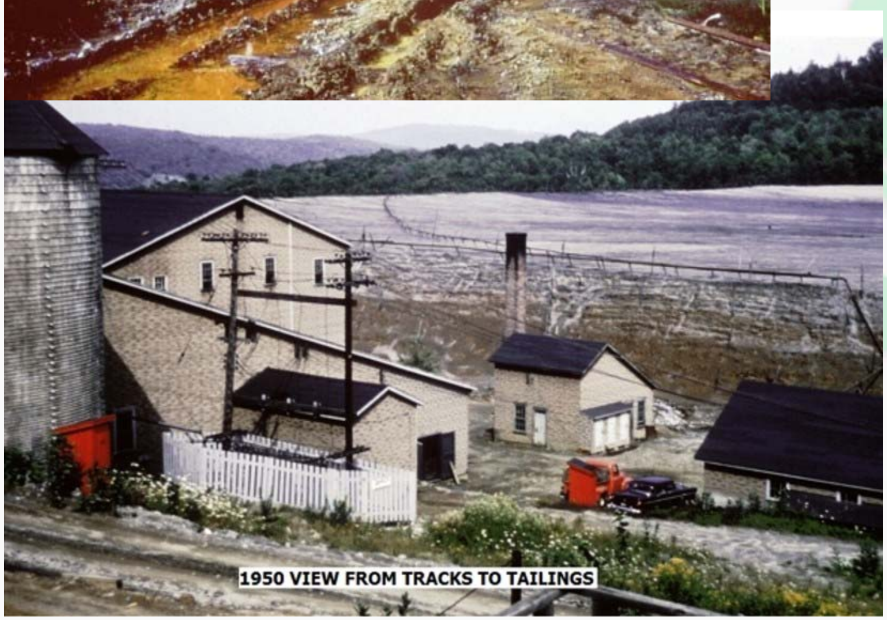
Site Industrial History

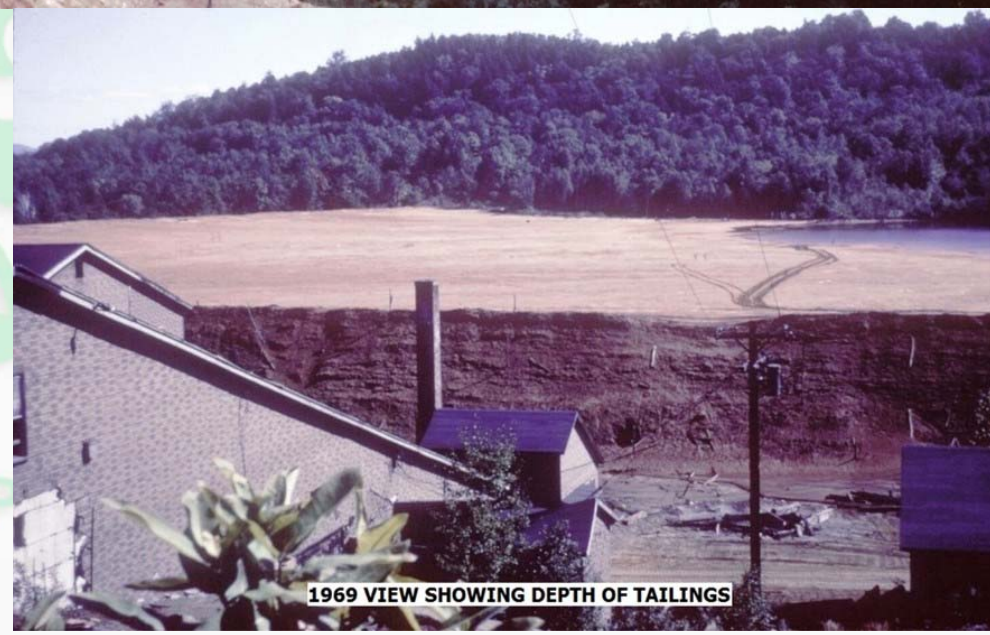
- Copperas Production
  - 1809 – 1882
    - 75% of U.S. production 1820's
    - About 30,000 tons total
    - About 200,000 cubic yards of waste material
- Copper Production
  - 1830 – 1942
    - 5,000 tons of copper
  - 1942-1958
    - 45,000 tons copper
    - 3 million tons of waste material
- Ceased operation in 1958 and divested property to local residents

Historical Photos



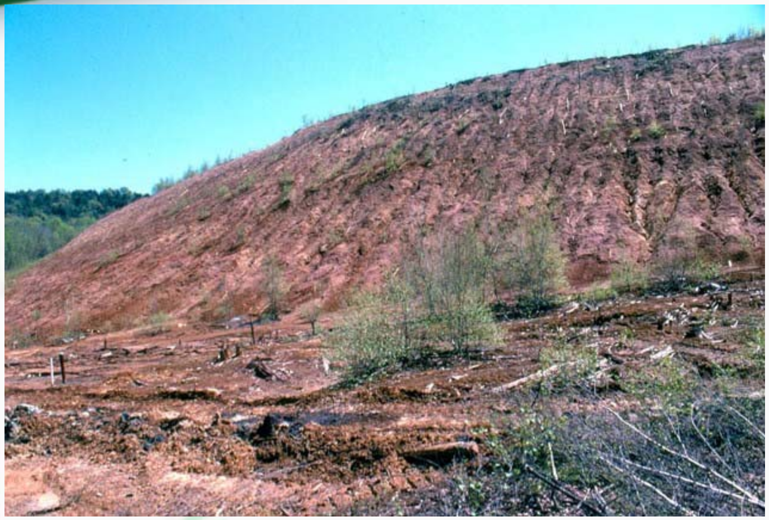






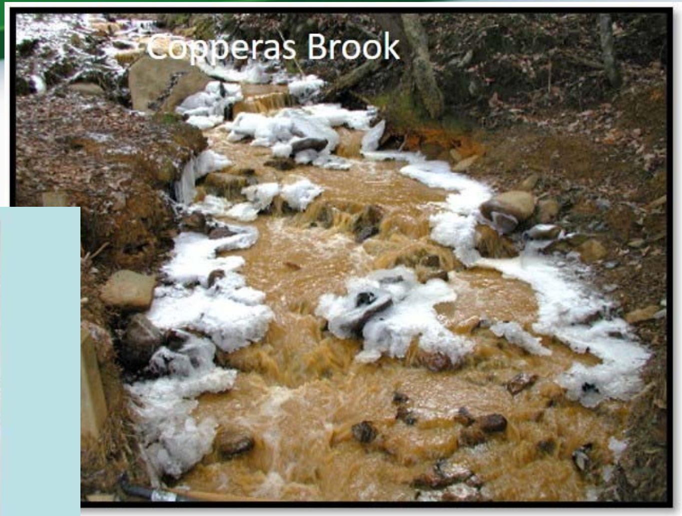
Tailings

Elizabeth Mine - Before Cleanup

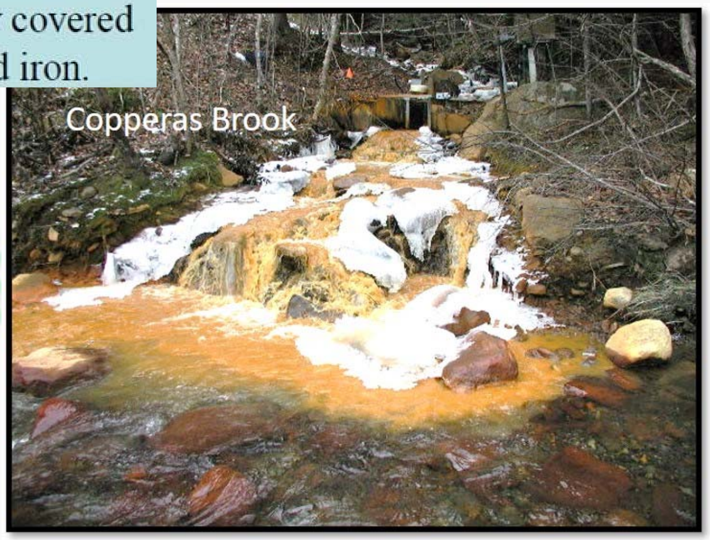


Remedial Investigation Outcome (01)

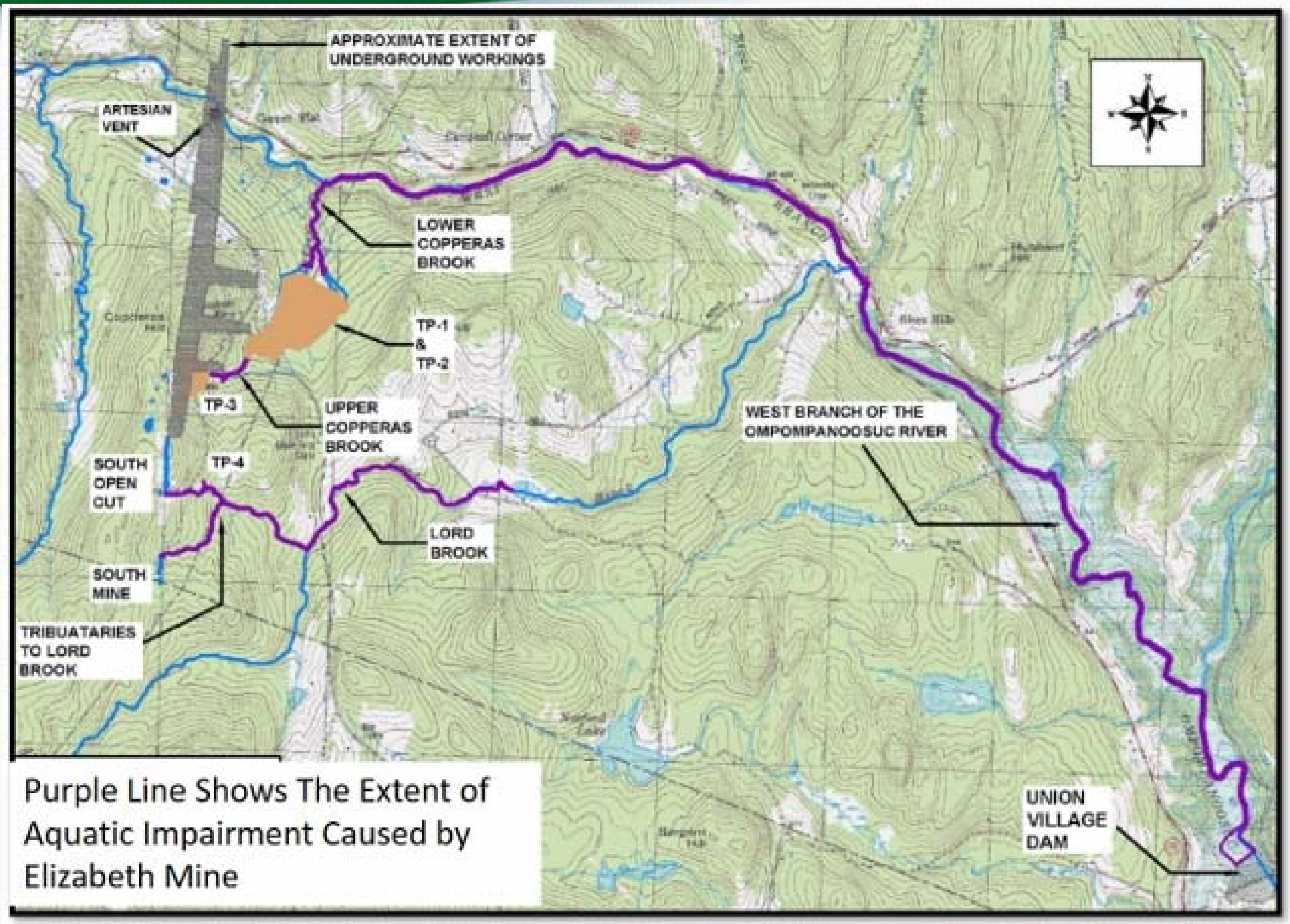
- Tailing dam for Tailing Pile 1 was unstable
- Five miles of aquatic impacts (copper, iron, zinc and pH)
  - Copper in Copperas Brook up to 100,000 ug/l vs 9 ug/l AWQC.
  - pH as low as 2 SU
  - Tailing Impoundment leachate contained iron up to 2,000,000 ug/l
- Sediment toxic to benthic organisms
- Lead in soil at Copperas Factories (up to 680,000 ppm lead in soil)
- Groundwater within underground workings (tunnels and shafts) and beneath waste areas unsuitable for human consumption (cadmium, cobalt, copper, iron, manganese, and zinc)




Stonefly Caddisfly covered with sediments and iron.



Remedial Investigation Outcome (02)



Purple Line Shows The Extent of Aquatic Impairment Caused by Elizabeth Mine

Clean-up Strategy

- Stabilize the Tailing Dam
- Source control actions to minimize the generation of mine influenced water (MIW) from waste rock piles and tailing impoundment
  - Consolidate waste rock onto impoundment
  - Install infiltration barrier cover system
  - Divert surface water and shallow groundwater
- Interim active treatment of the high leachate load
- Long-term passive treatment of residual leachate flow after source control actions

Tailing Dam Stabilization

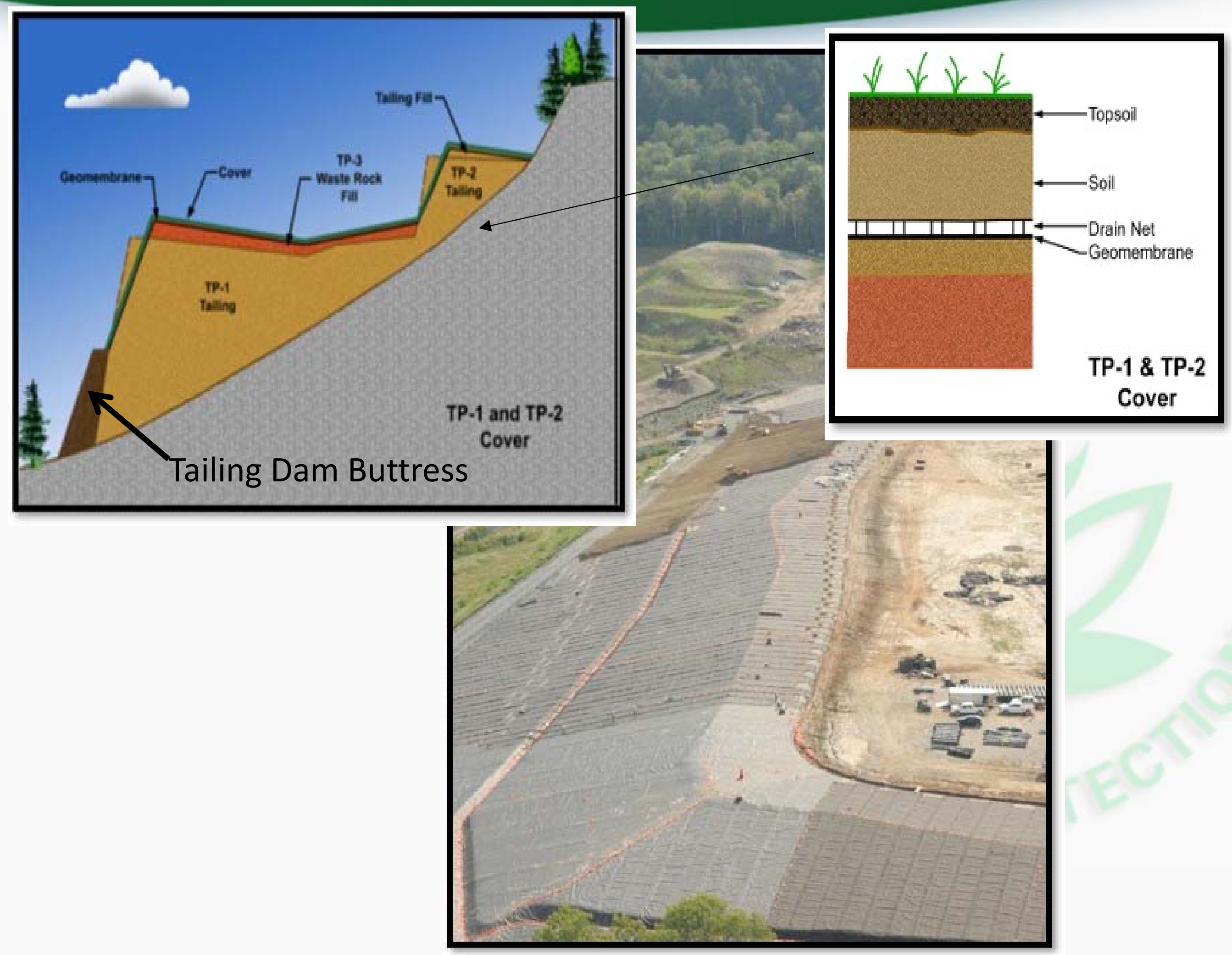
Installation of toe drain to allow tailing impoundment to drain after buttress installation

Tailing Dam Stabilization – Construction of Buttress

Source Control Actions - Before

Source Control Actions - After

Source Control Actions – Cover



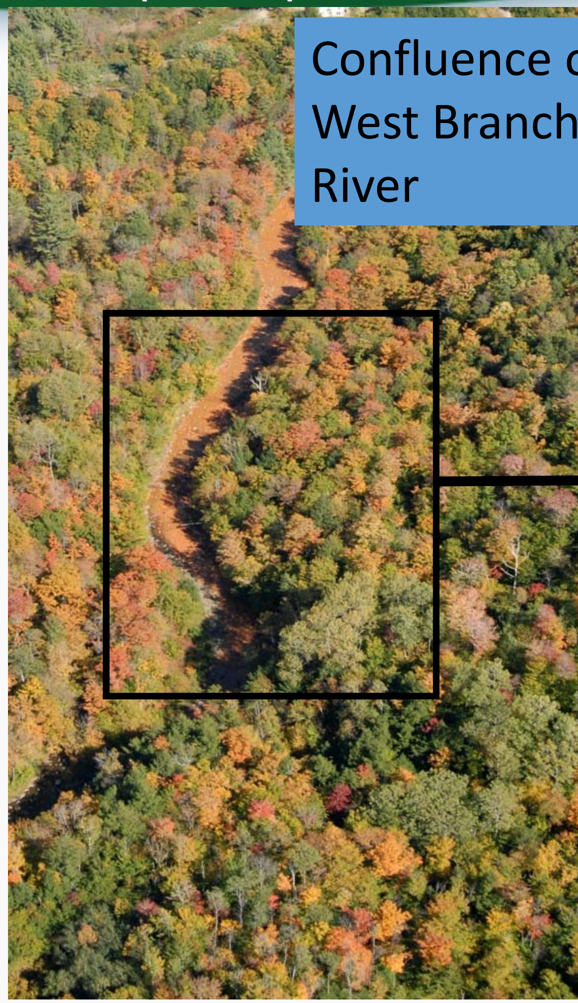
TP-1 and TP-2 Cover System

- Cover the tailing and 400,000 cubic yards of other waste material consolidated from other locations on site
- Additional 100,000 cubic yards of tailing excavated to achieve final slope grades
- 45 acres
- Solar development “friendly”
- 153,000 cubic yards of soil on cover system
- 2 million square feet (each) of geomembrane, drainage geocomposite, and seed mix

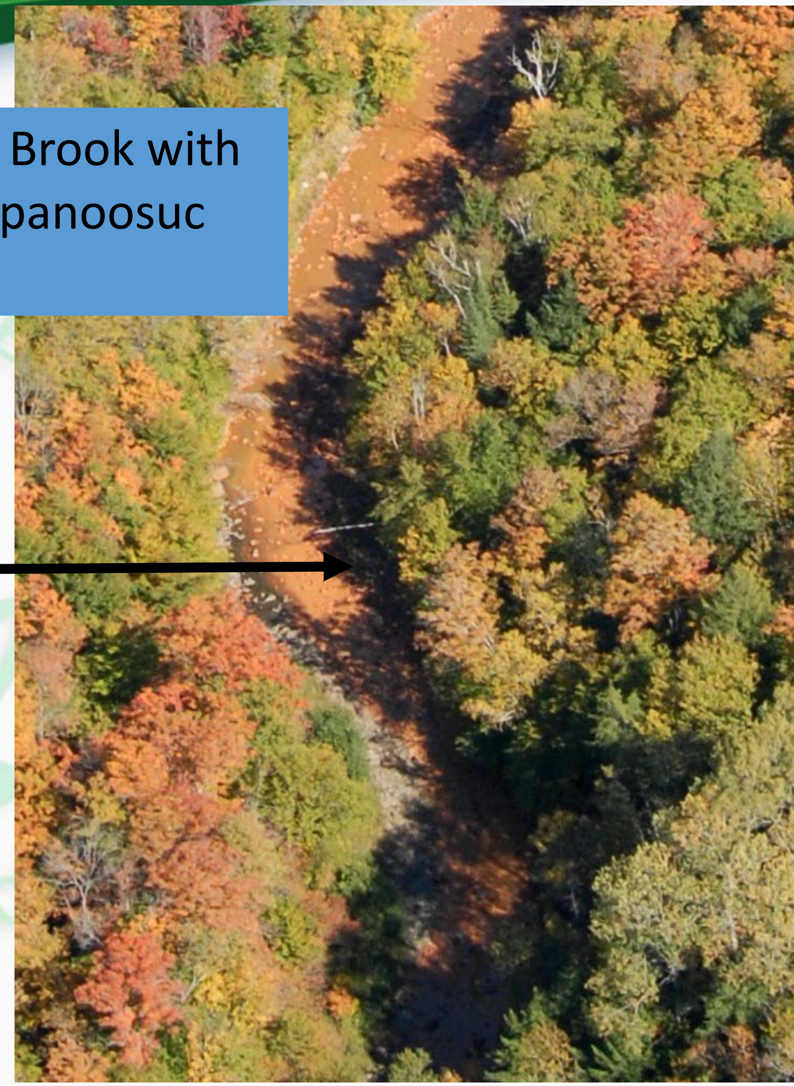
Source Control Actions - Diversions

Blue lines show surface water/shallow groundwater diversion channels installed around the Tailing Impoundment

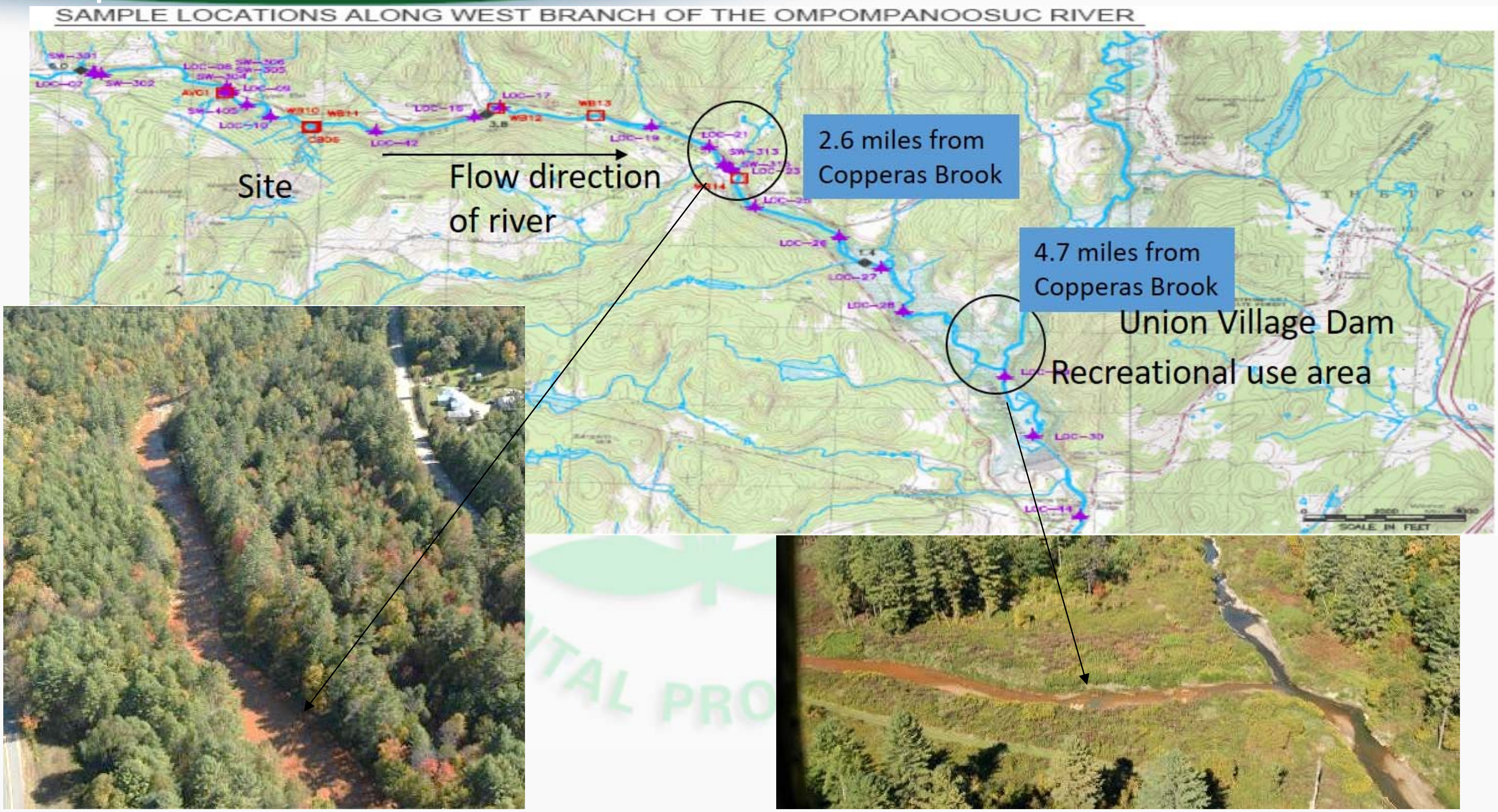
Leachate Influence – Copperas Brook Confluence with West Branch Ompompanoosuc River



Confluence of Copperas Brook with West Branch of Ompompanoosuc River

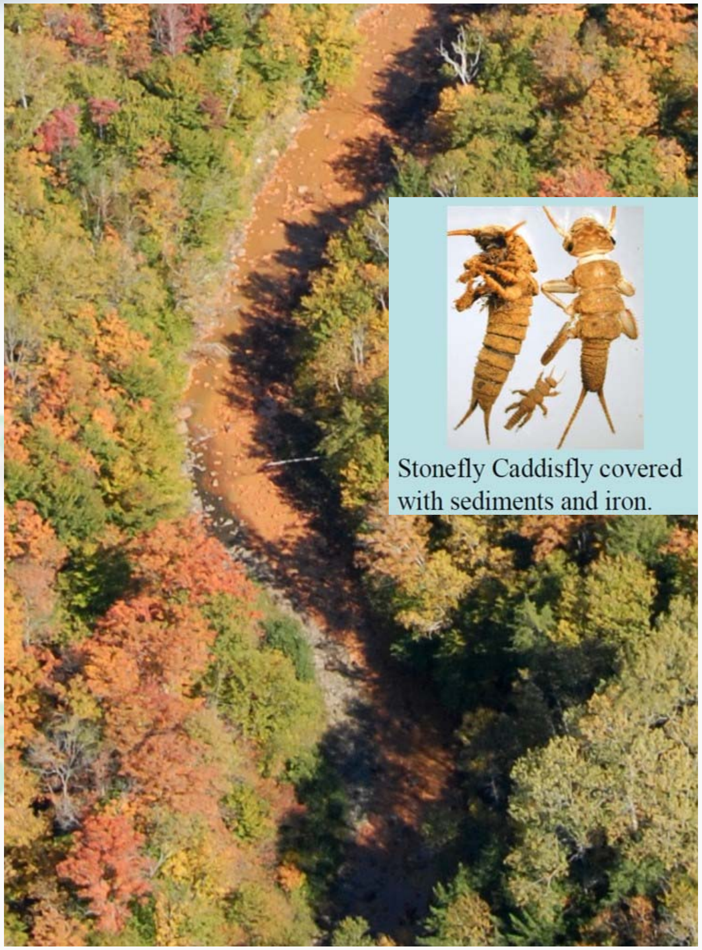


Leachate Influence – West Branch Ompompanoosuc River



Leachate Treatment – Problem Statement

- Iron leachate was creating acidity, smothering the benthic environment, and creating a visual impact for several miles
- Stakeholders wanted to see the water quality improvement as soon as possible
- Source control actions require time to impact the leachate flow and decrease the iron load
- EPA sought to implement a treatment technology that could provide an effective interim solution until a passive treatment system could be constructed



Leachate Treatment – Site Characteristics

- Determining characteristics
  - Limited physical space and steep topography
  - Extended periods of cold weather
  - High iron load (up to 800 lbs/day)
  - Significant precipitation events
  - Electrical power was available

Outline (02)

- Elizabeth Mine site history
- **Water treatment for ferrous iron**
- RCTS™ system and comparison to conventional lime treatment
- RCTS™ at Elizabeth Mine
- Lessons learned
- Final remarks

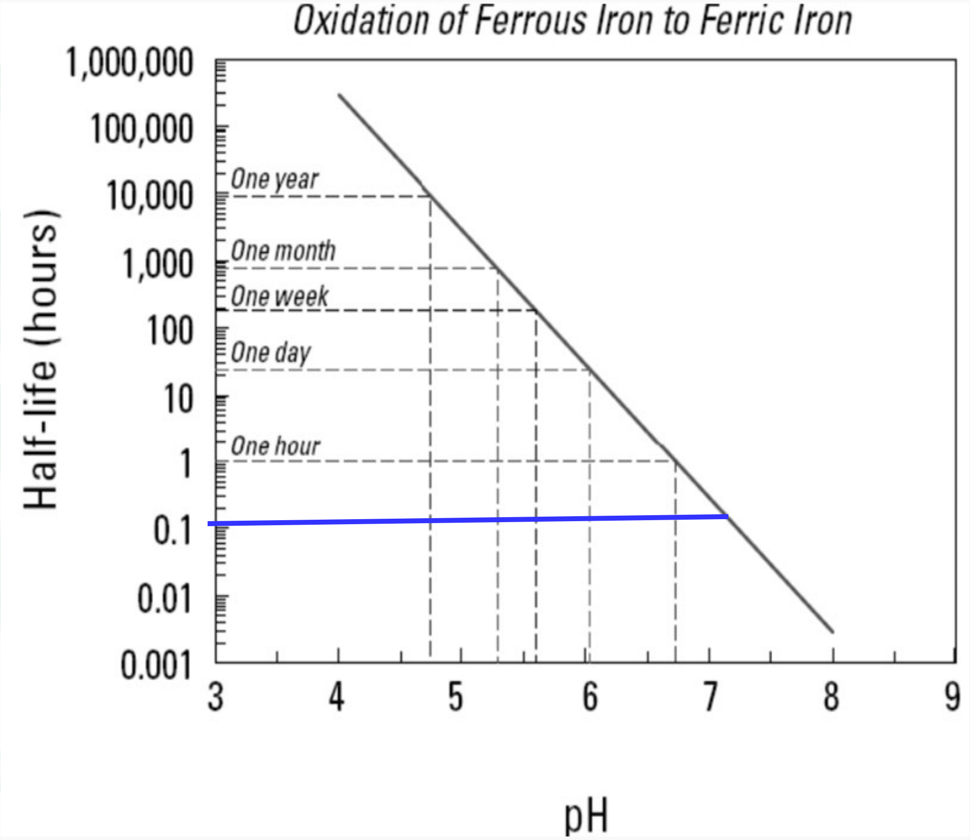
Water Treatment – Ferrous Iron (01)

- Typically involves adding oxygen to oxidize ferrous iron to ferric iron and increasing pH to above ~ 3.5, commonly with lime or slaked lime
  - $O_2\ (g) + 4Fe^{2+}\ (aq) + 4H^{+}(aq) \rightarrow 4Fe^{3+}\ (aq) + 2H_2O\ (l)$
  - $CaO(s) + H_2O\ (l) \rightarrow Ca(OH)_2(s)$
  - $3Ca(OH)_2\ (s) + 2Fe^{3+}\ (aq) \rightarrow 3Ca^{2+}(aq) + 2Fe(OH)_3\ (s)$

- Ferrous hydroxide also will precipitate with addition of lime (pH > 8), but will oxidize to ferric when exposed to oxygen
  - $Ca(OH)_2\ (s) + Fe^{2+}\ (aq) \rightarrow Ca^{2+}(aq) + Fe(OH)_2\ (s)$

Water Treatment – Ferrous Iron (02)

- Abiotic oxidation rate of ferrous (Fe^{2+}) to ferric (Fe^{3+}) iron, modified from Stumm and Lee, 1961
- $-d[Fe^{2+}]dt = k_{Fe}[Fe^{2+}][O_2(aq)][OH^-]^2$
  - At pH 7, oxidation from Fe^{2+} to Fe^{3+} takes only minutes



Water Treatment, Continued

- General preference for lime over sodium hydroxide (NaOH)
  - Denser sludge
  - Higher neutralization capacity
  - NaOH requires more careful storage and handling
    - Reactive caustic liquid
    - Freeze protection
  - Lime allows slower changes in pH with each incremental dose
  - May be concerns with discharge of large quantities of sodium

Outline (03)

- Elizabeth Mine site history
- Water treatment for ferrous iron
- **RCTS™ system and comparison to conventional lime treatment**
- RCTS™ at Elizabeth Mine
- Lessons learned
- Final remarks

Water Treatment – RCTS™

- Conventional lime treatment plants
  - Mixers in reaction tanks to form a slurry
  - Compressors, diffusers, and agitators to provide oxygen
- Rotating cylinder treatment system (RCTS™)
  - Developed by Ionic Water Technologies, Inc.
  - More compact and mobilizable
  - Replaces conventional agitators, compressors, diffusers, and reaction tanks with perforated cylinder that rotates through a trough containing the lime slurry and the water to be treated

Sources: Tsukamoto and Moulton, 2006; Tsukamoto and Weems, 2010

Water Treatment – RCTS™

- Rotating cylinder treatment system (RCTS™)
  - Film of water adheres to the inner and outer surfaces of the cylinder as it rotates
  - Oxygen exchange occurs and agitation by impact of perforations with water enhances lime mixing and dissolution, and oxygen transfer

Source: Tsukamoto and Moulton, 2006

Water Treatment – RCTS™ (01)

- Direct comparison to conventional lime treatment at Leviathan Mine, CA
  - Lime consumption
    - Conventional = 180.5 kg/day
    - RCTS™ = 105.7 kg/day
  - Dissolved oxygen concentration in effluent
    - Conventional = 4.22 mg/l
    - RCTS™ = 7.86 mg/l
  - Hydraulic residence time
    - Conventional = 131.7 min
    - RCTS™ = 58.5 min
  - Energy consumption
    - Conventional = 8640 W
    - RCTS™ = 2640 W

Source: Tsukamoto and Weems, 2009

Outline (04)

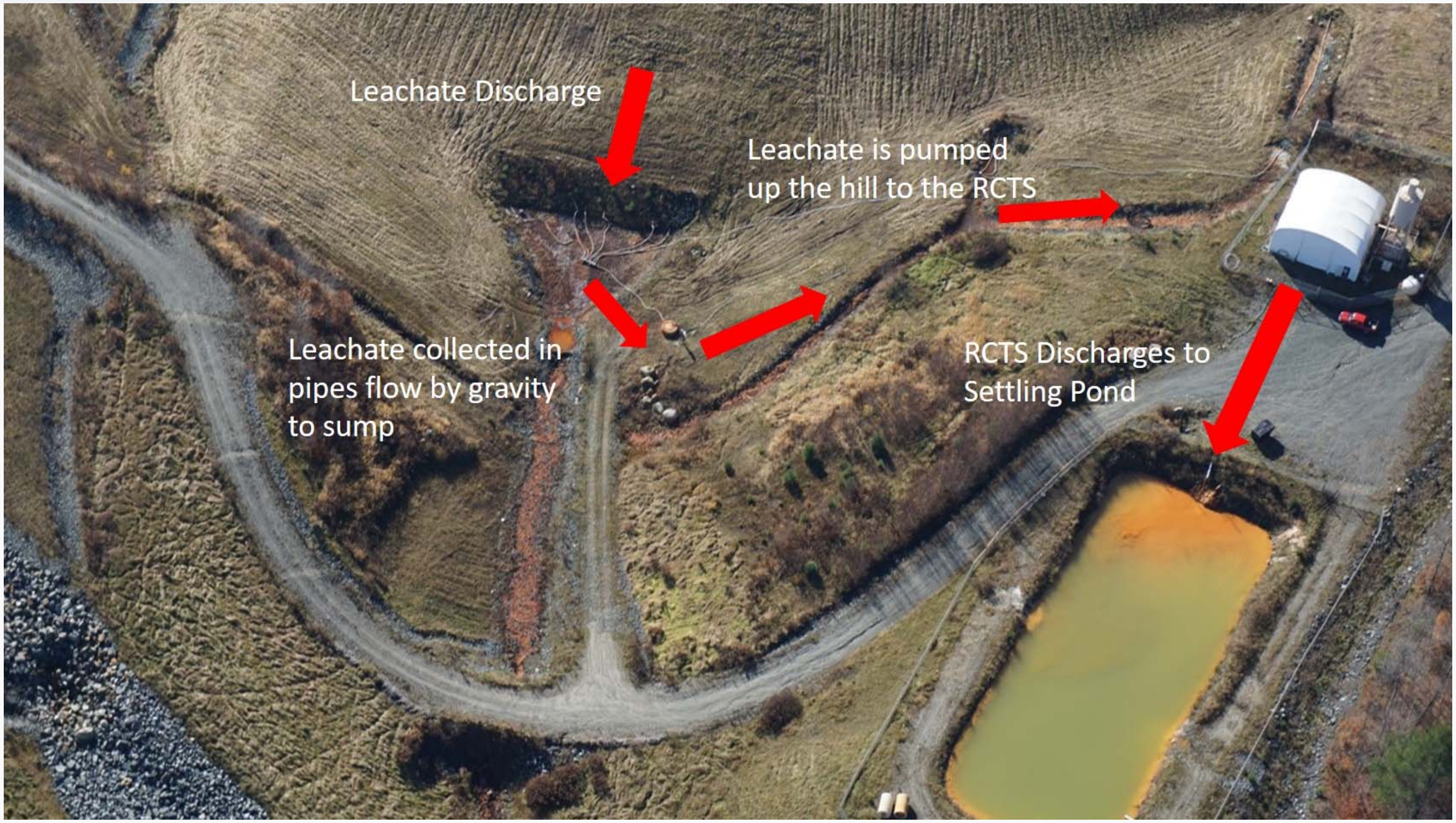
- Elizabeth Mine site history
- Water treatment for ferrous iron
- RCTS™ system and comparison to conventional lime treatment
- **RCTS™ at Elizabeth Mine**
- Lessons learned
- Final remarks

RCTS™ Design at Elizabeth Mine

- RCTS™ chosen
  - Relatively small footprint
  - Ability to handle high iron load
- Operate April-November
  - Insulating and heating of building would have been expensive and difficult to keep water from freezing before and after treatment
- Average influent flow 6.8 m^3/hr (30 gpm)
- Maximum influent flow 9.1 m^3/hr (40 gpm)
- Average influent iron concentration 900 mg/l
- Maximum effluent iron concentration < 50 mg/l
- Anticipated operational life of 5 years
  - But operated for 10 years

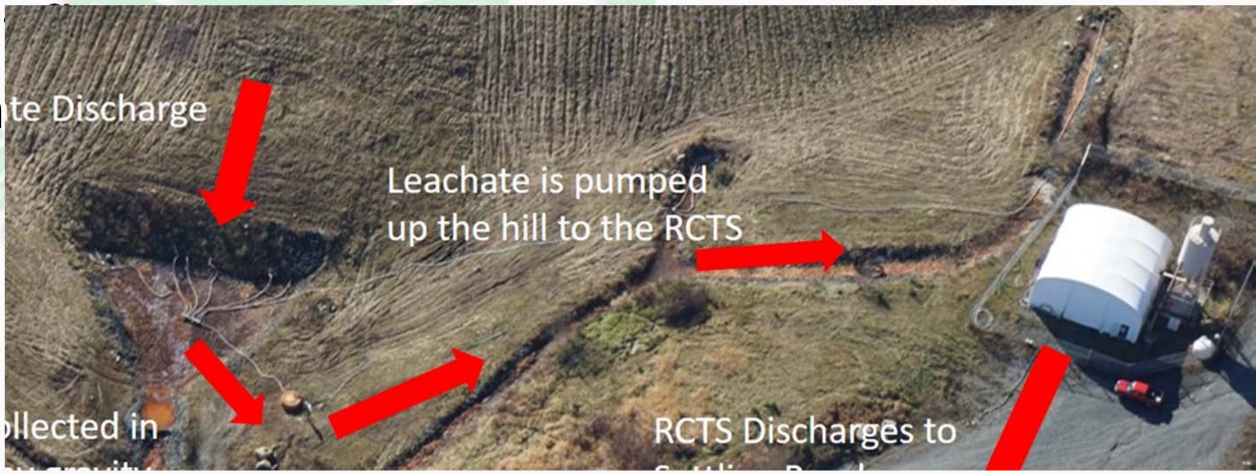
Active Treatment System Components

- Collection
- Neutralization
- Aeration
- Precipitation
- Settling

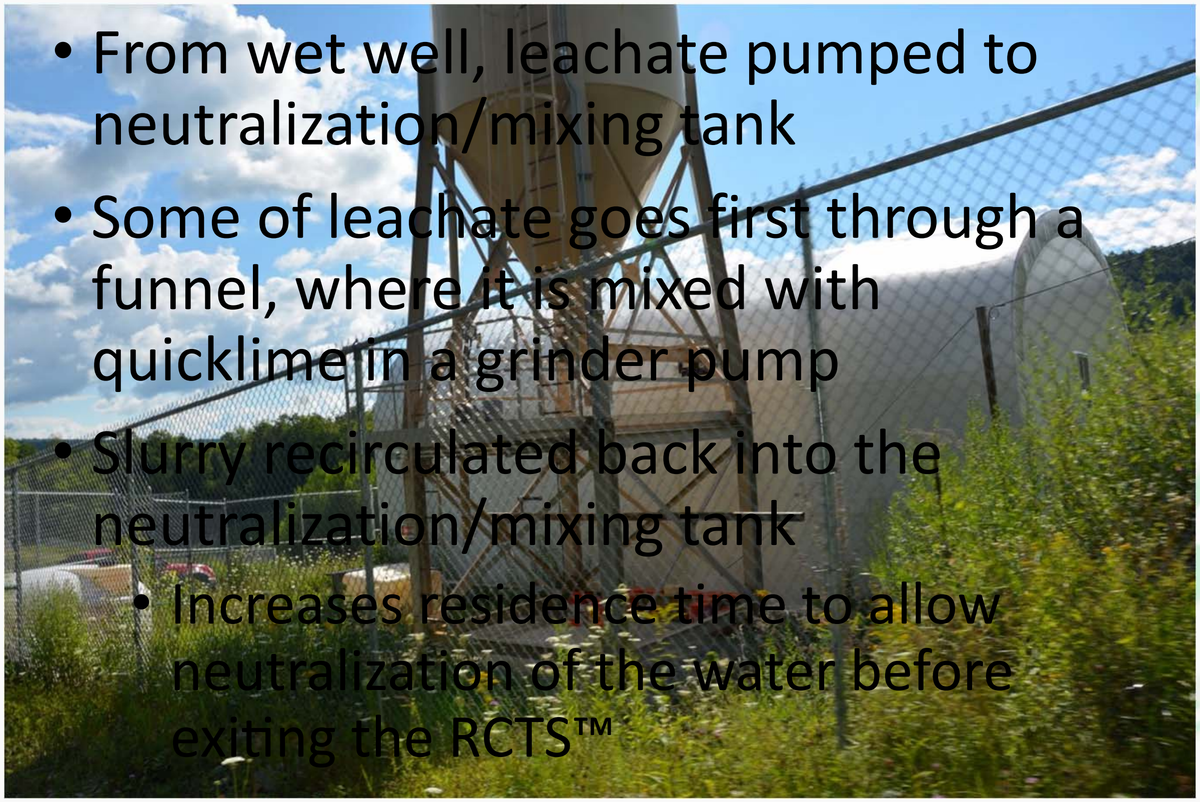


Leachate Collection

- Combined toe and horizontal drain leachate to a manifold that drains by gravity into a pump station wet well
- System flow controlled by floats in the pump station.
- The pumps operate at a higher rate than the leachate flow from TP-1 to maintain a wet well level, which results in intermittent operation over the course of each day and differences in leachate flows measured versus treatment influen
  - Typical sump operation



Neutralization



- From wet well, leachate pumped to neutralization/mixing tank
- Some of leachate goes first through a funnel, where it is mixed with quicklime in a grinder pump
- Slurry recirculated back into the neutralization/mixing tank
  - Increases residence time to allow neutralization of the water before exiting the RCTS™

RCTS™ Aeration

- From neutralization/mixing tank, water flows by gravity to the RCTS™ unit
  - Aerated as thin layer of water around inside of 2 rotating cylinders

Precipitation & Settling

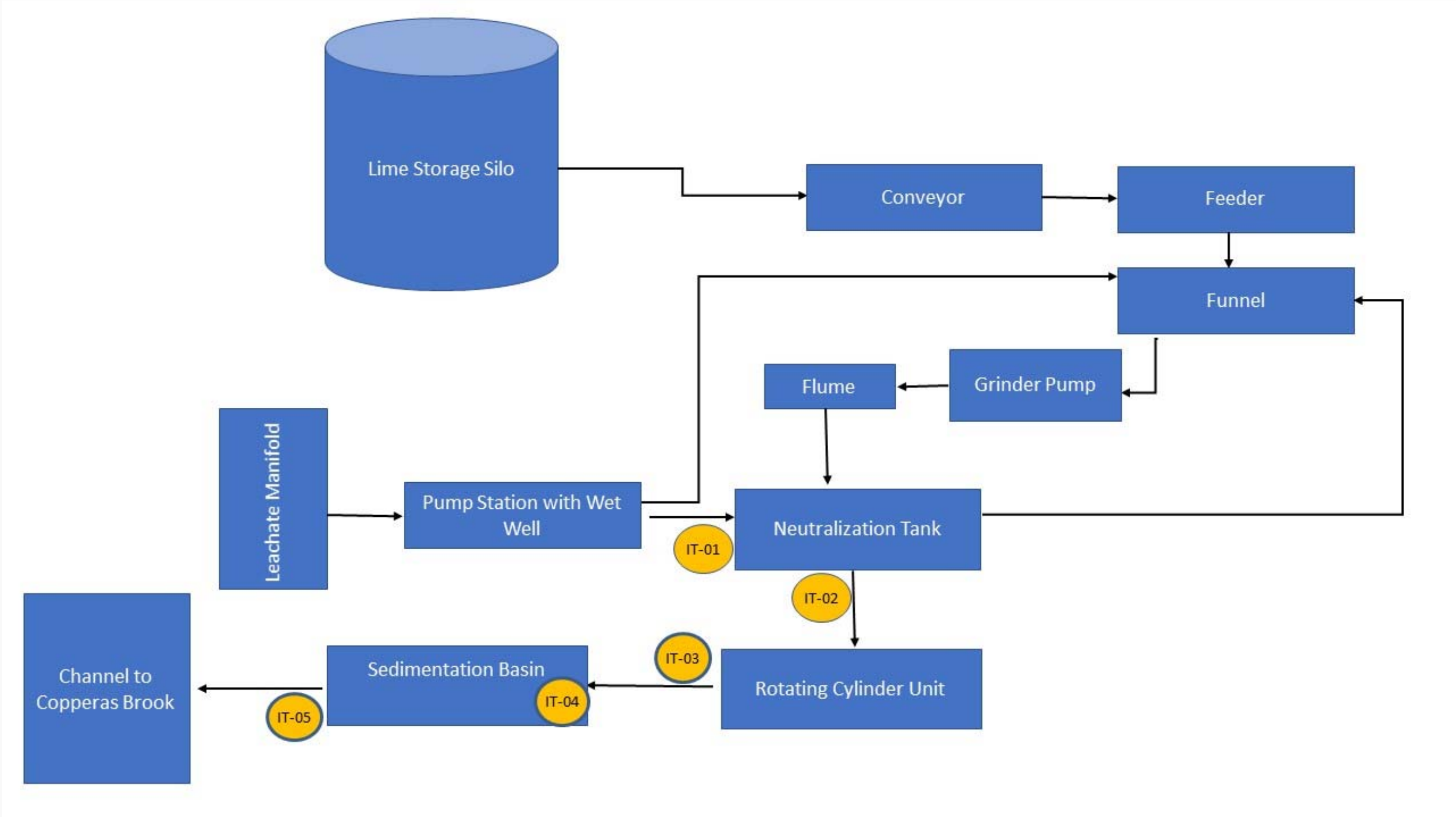
- Aerated, alkaline water gravity fed from the RCTS™ to the sedimentation basin

Operation and Maintenance

- Maintaining equipment in accordance with manufacturer’s instructions
- Maintaining accurate records of data from operations
- Process operation monitoring using field analytical methods
- Removing precipitates from component systems
- Troubleshooting and repairing/replacing faulty equipment
- Seasonal operation required commissioning and decommissioning each year

Schematic with Sampling Locations

- 2009 – 2017
  - At least once per month April-Nov
- IT-01, IT-03, IT-05
  - Unfiltered total iron (ferrous + ferric); filtered ferrous iron; pH

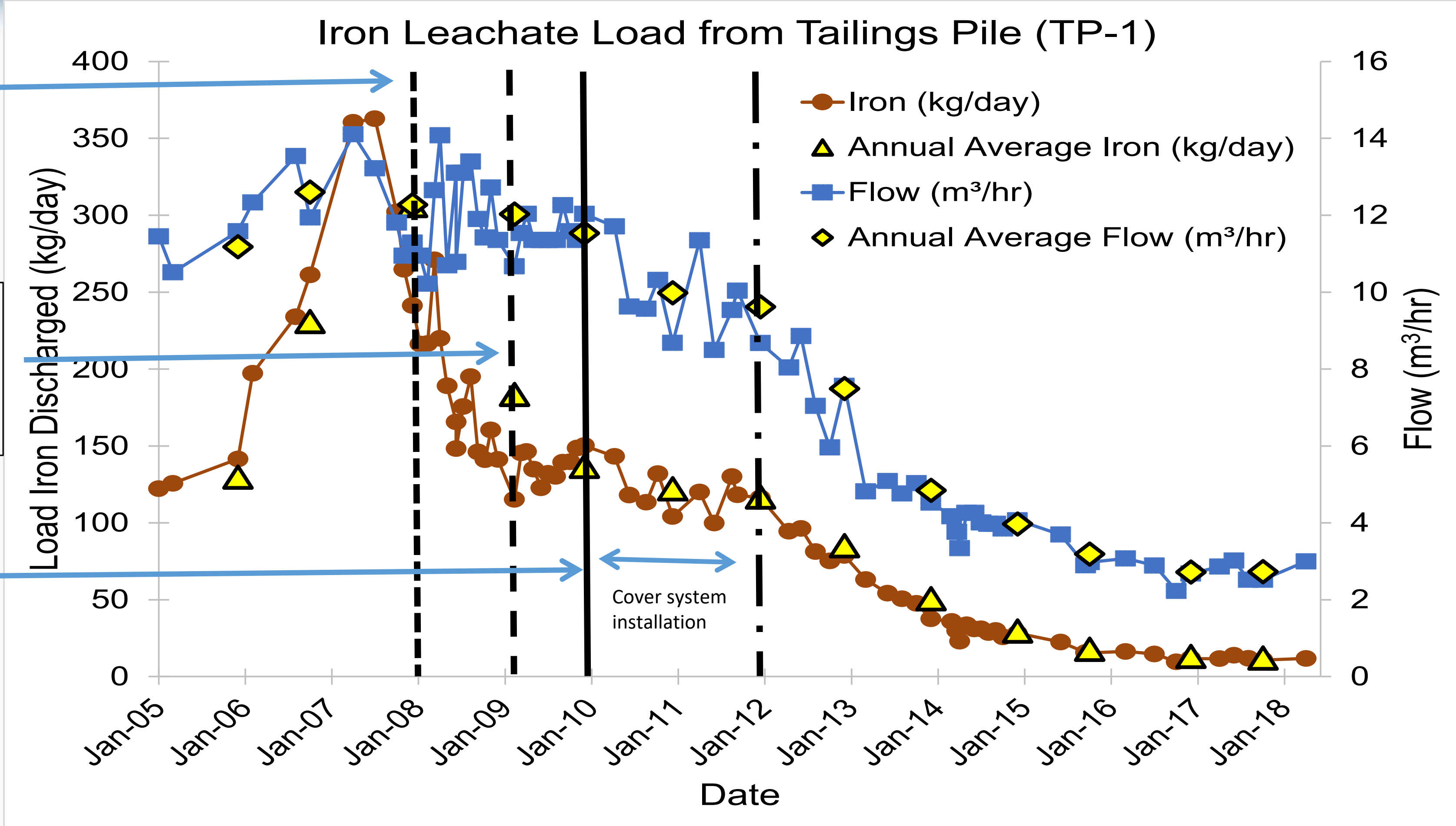


Leachate Iron Load from TP-1

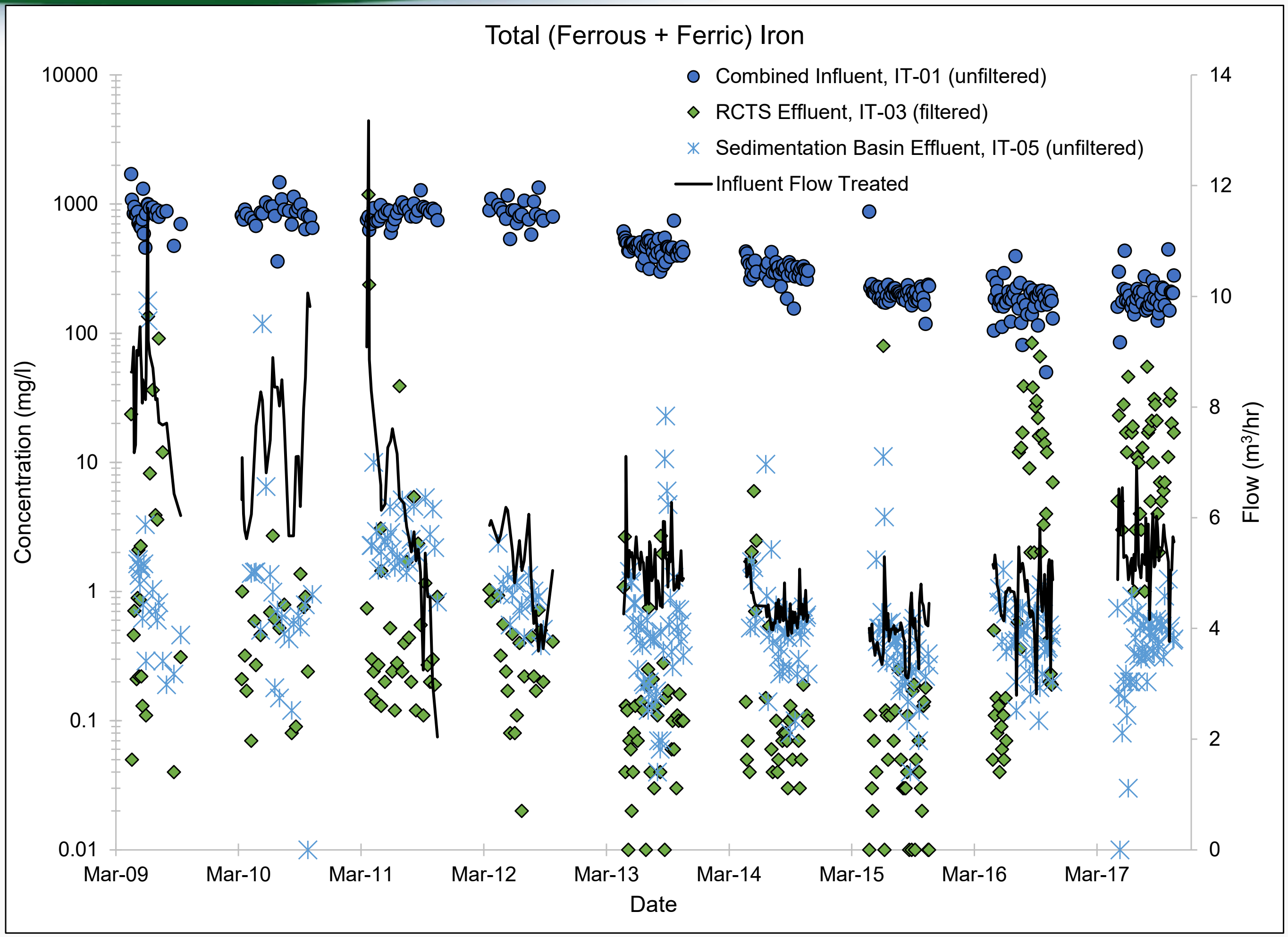
Horizontal drain Installation and surface water diversion

Waste Rock Consolidation and Surcharge

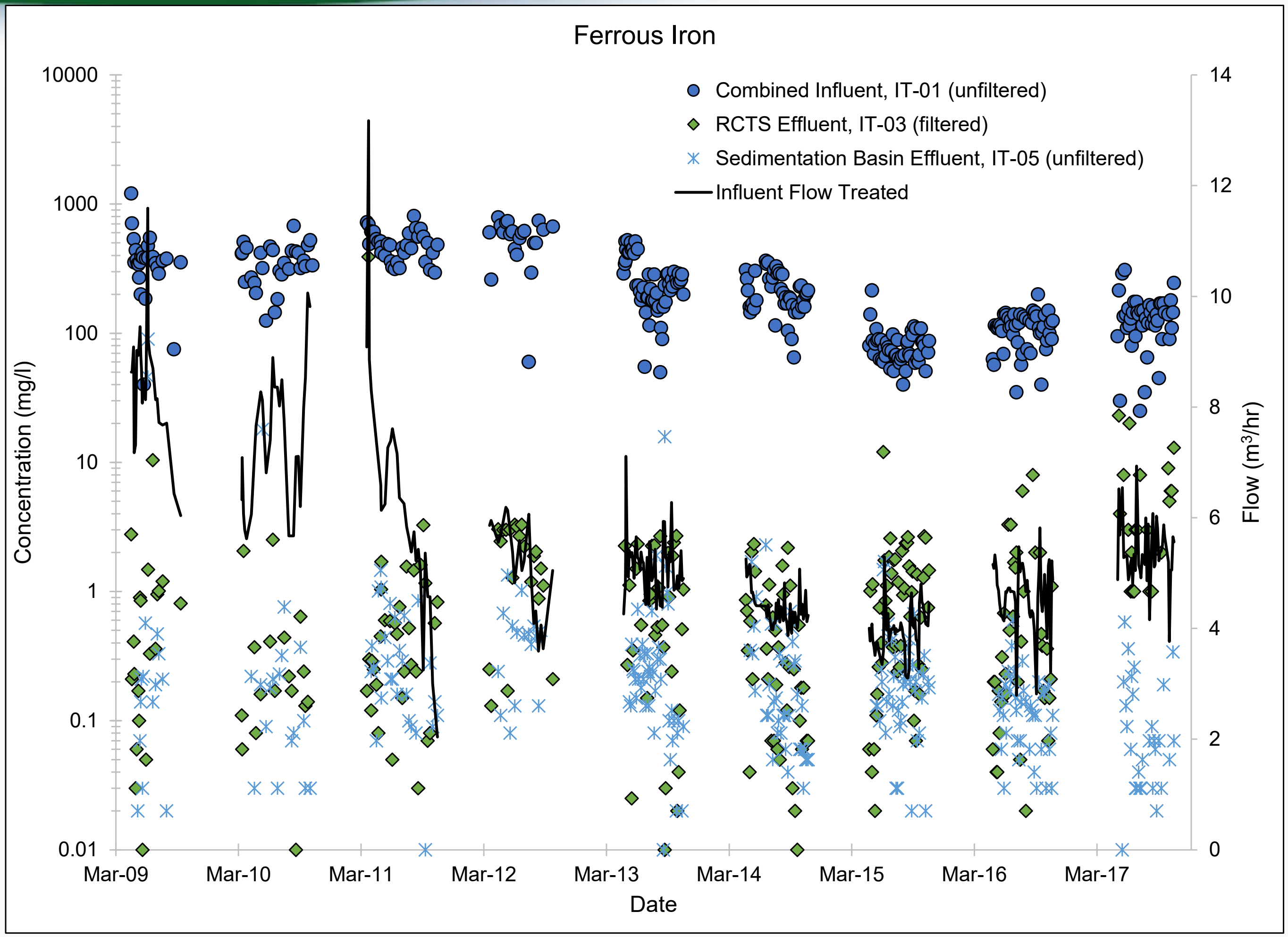
Cover system Installation



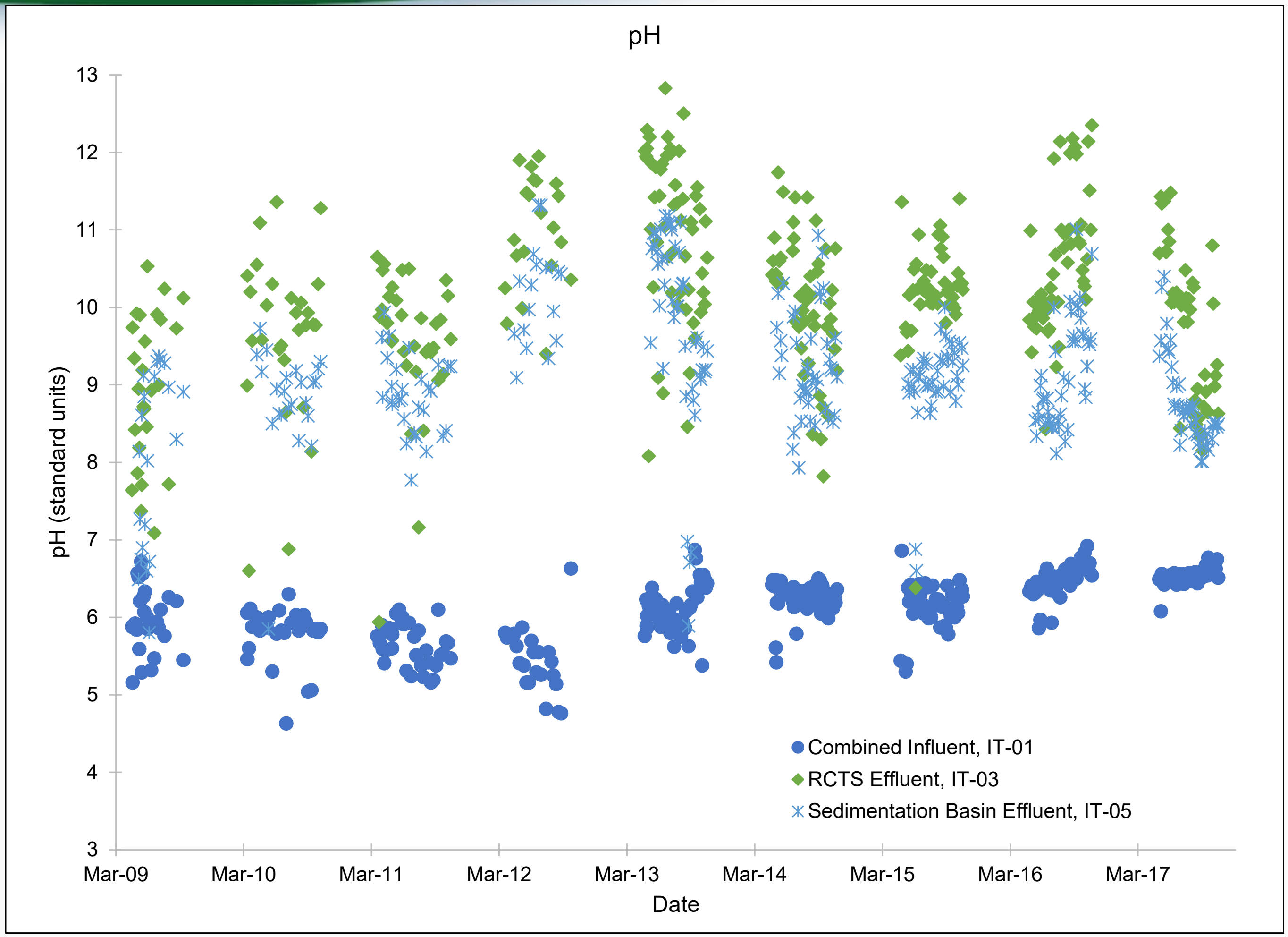
Total Iron (Ferrous + Ferric) Field Concentrations



Ferrous Iron Field Concentrations

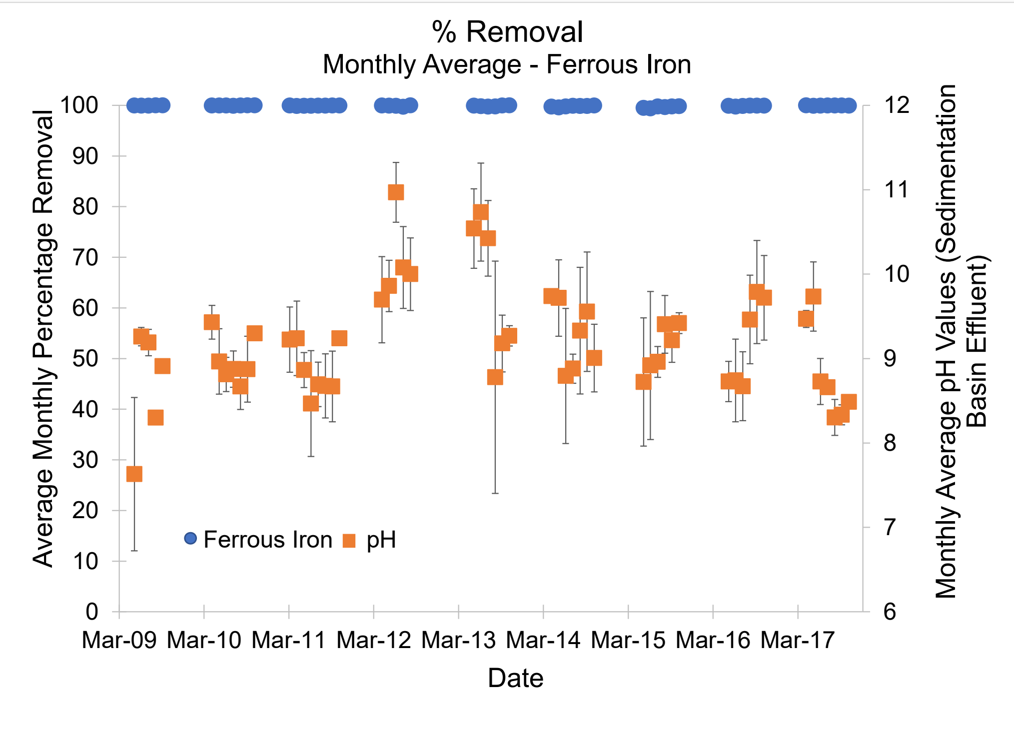


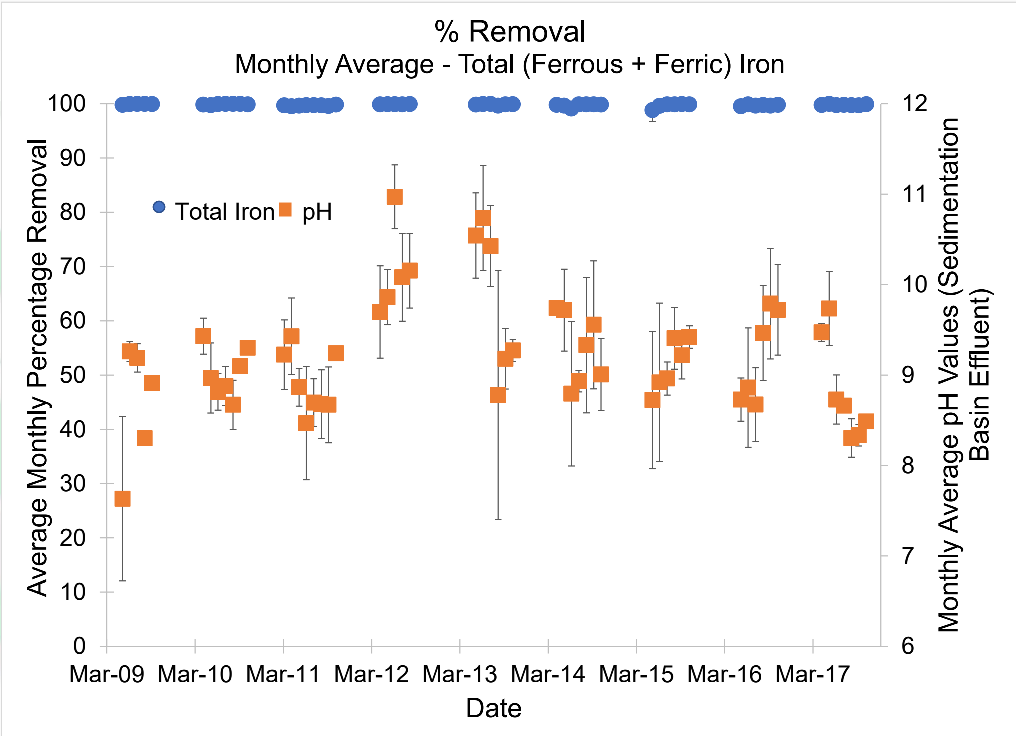
Field pH



pH
pH (standard units)
13
12
11
10
9
8
7
6
5
4
3
Mar-09
Mar-10
Mar-11
Mar-12
Mar-13
Mar-14
Mar-15
Mar-16
Mar-17
Date
Combined Influent, IT-01
RCTS Effluent, IT-03
Sedimentation Basin Effluent, IT-05

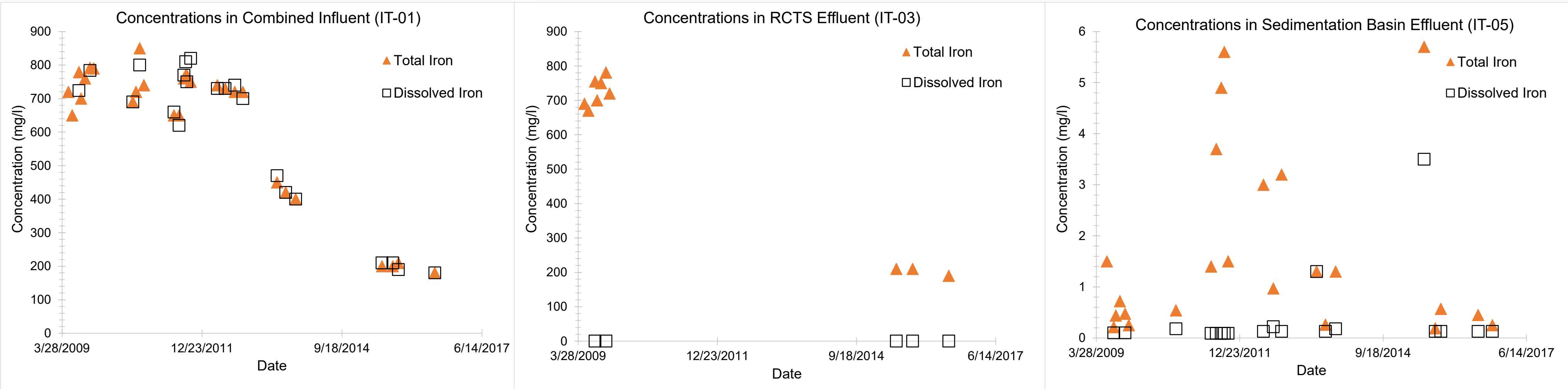
% Removal – Field Data





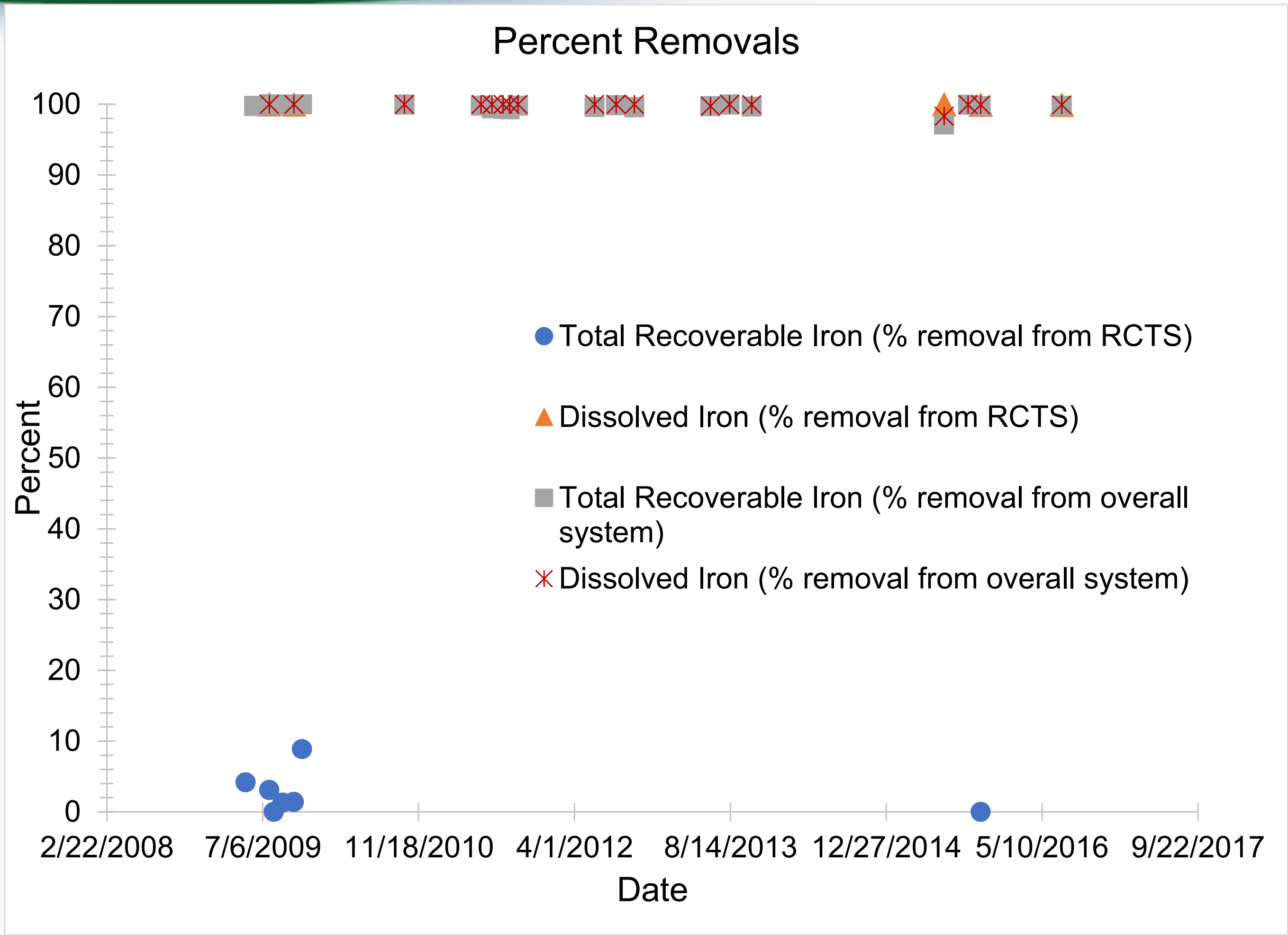
Removal %=100×($influent\ concentration$ (IT−01) −$sedimentation\ basin\ effluent\ concentration$ (IT−05)) / $influent\ concentration$ (IT−01)

Iron Concentrations – Laboratory Data



- Total recoverable (unfiltered)
- Dissolved (filtered at 0.45 um)

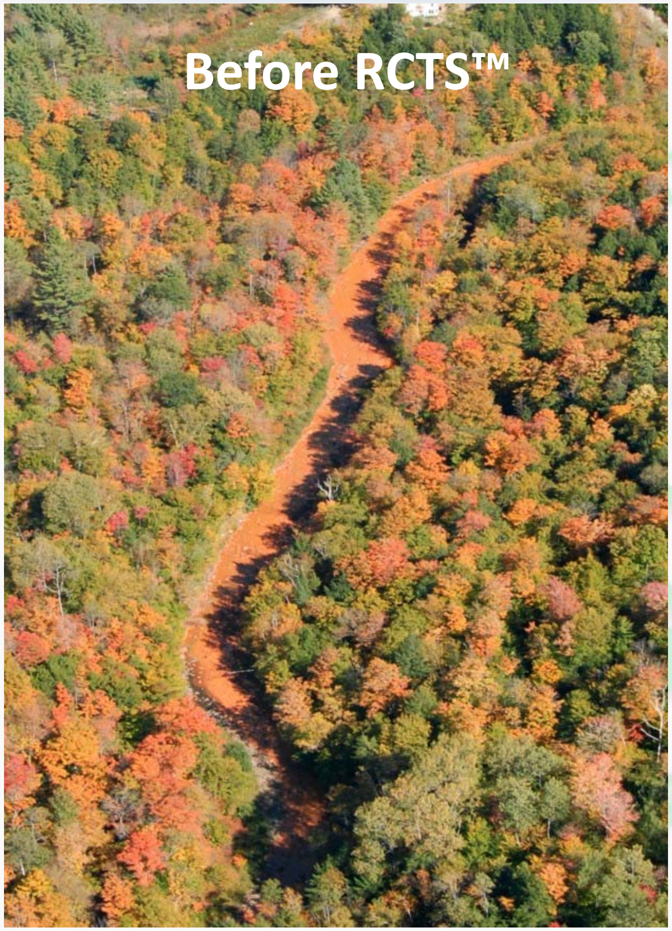
% Removal – Laboratory Data

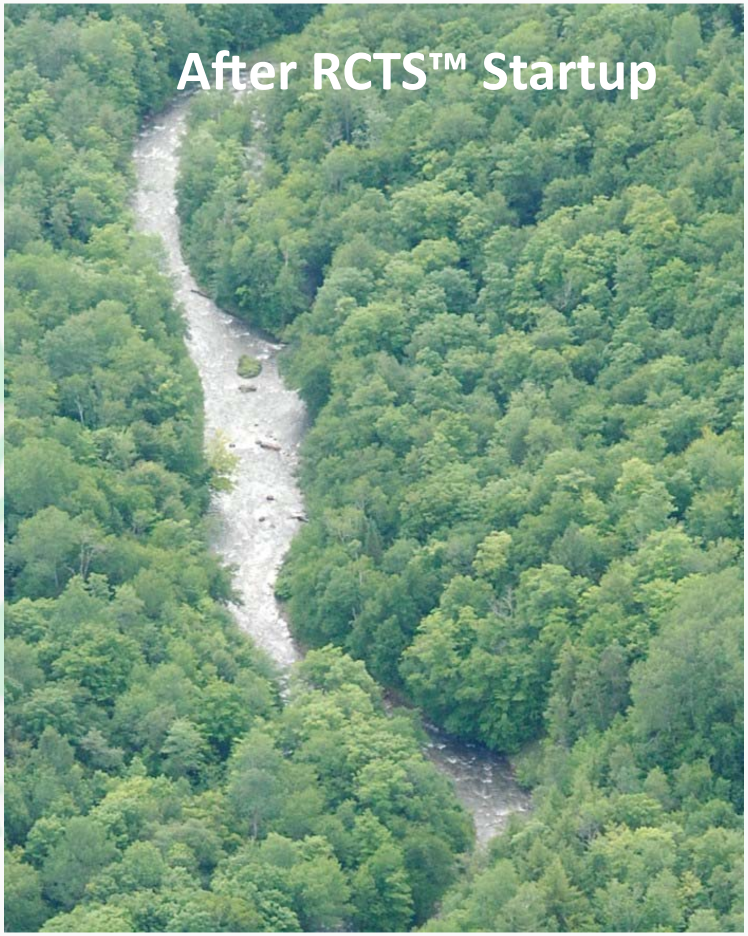


Dissolved Oxygen – 2009

- Dissolved oxygen
  - < 1 mg/l to ~ 12 mg/l over 2007 – 2010 in leachate drains
  - 2009
    - Influent to RCTS™ average 4.3 mg/l; range 2.7 – 5.5 mg/l
    - RCTS™ effluent average 6.4 mg/l; range 5.0 – 7.6 mg/l
      - ~ 2 mg/l increase from the RCTS™
    - Sedimentation basin average 6.3 mg/l; range 4.3 – 9.1 mg/l

Visible Improvements in Watershed





Outline (05)

- Elizabeth Mine site history
- Water treatment for ferrous iron
- RCTS™ system and comparison to conventional lime treatment
- RCTS™ at Elizabeth Mine
- **Lessons learned**
- Final remarks

Lessons Learned

- Gypsum, gypsum, gypsum!
  - Ca^{2+} released will react with sulfate to form gypsum when sulfate is > about 1,500 – 2,000 mg/l
  - Causes scaling and plugging
- Scaling and plugging affected nearly all components of the system
  - Clogged pipes and clogged outlets
  - Cracking of seams in RCTS™ drums
  - Failed bearings from being out of balance from scale buildup
  - Blocking of sedimentation basin effluent pipe
  - One clogged pipe melted
    - Reaction of lime with water is exothermic

Lessons Learned (02)

- Plumbing and equipment should be as accessible as possible to allow for easier maintenance
- Design should consider potential future upgrades
- Pumps should be configured to allow use of universal motors
- Many factors need to be considered together in optimizing both efficiency and costs
  - Identifying and understanding required specifications for piping and other components contacting lime
  - Identifying ways to minimize complications of gypsum formation

Lessons Learned (03)

- Important to closely monitor pH
  - Assure sufficient neutralization followed by effective aeration with minimal scaling
- Monitoring ferrous iron allows assessment of oxidizing performance, but monitoring DO may also be helpful in assuring sufficient oxidation
  - Although some further oxidation occurs in the sedimentation basin, efficiency is dependent on surface area for oxygen transfer

Lessons Learned (04)

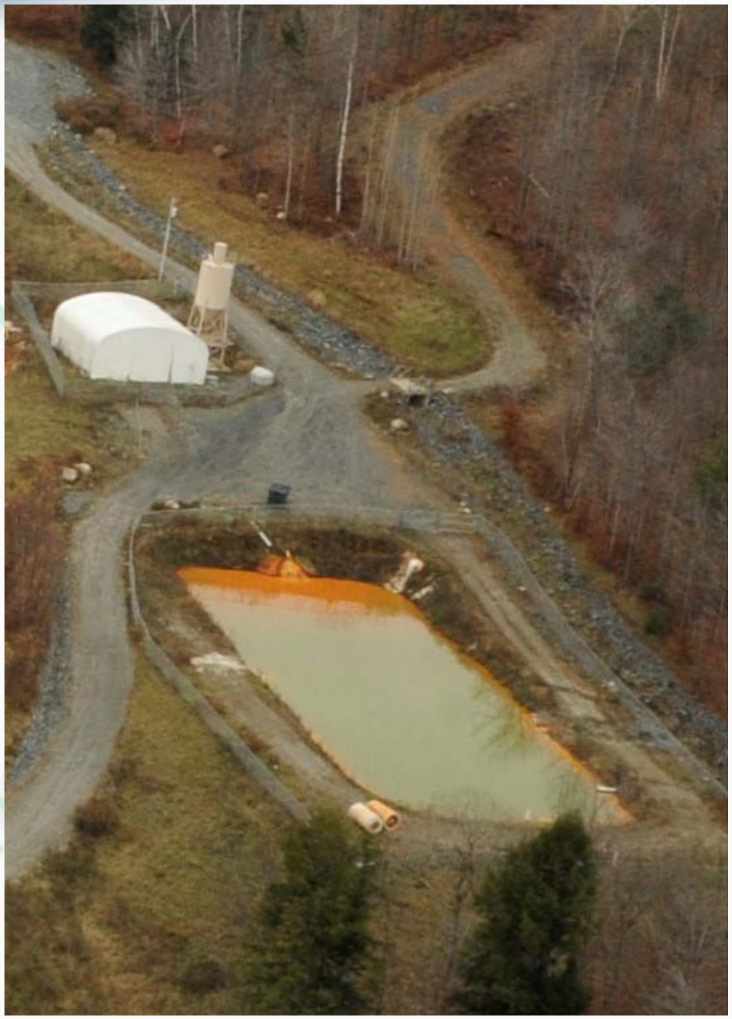
- Sludge storage can be a challenge
  - Trespass potential?
    - Consistency doesn't support being walked upon
- Sludge disposal can be a challenge
  - Dispose on site? Any hazardous constituents requiring off-site disposal of a dry cake?
- Consider costs to allow sufficient funds for replacement items to avoid loss of treatment capability
  - This system was designed to last 5 years, but lasted 10
    - However, the neutralization tank and the RCTS™ drums were approaching the end of their useful life

Outline (06)

- Elizabeth Mine site history
- Water treatment for ferrous iron
- RCTS™ system and comparison to conventional lime treatment
- RCTS™ at Elizabeth Mine
- Lessons learned
- **Final remarks**

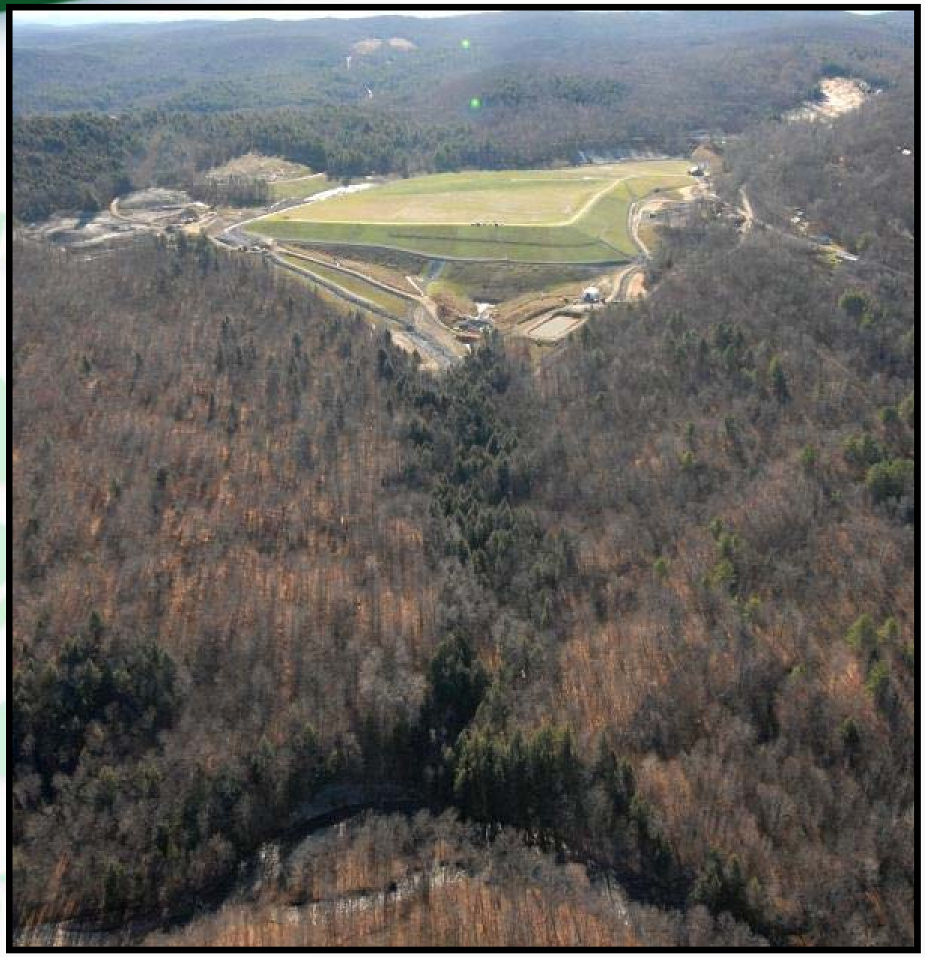
Final Remarks – TP-1 Treatment

- The temporary treatment system provided effective treatment for 10 years
  - Sedimentation basin effluent concentration generally < 1 mg/l, with wide range of RCTS™ influent concentrations over the 8 years of data analyzed
- Treated 50,818,799 gallons of leachate from 2008-2018
- Leachate iron load is much lower today than in 2007
  - Average 10.9 kg/day (24 lb/day) vs max of 363 kg/day (800 lb/day)



Final Remarks – All Site Activities

- Tailing dam stabilized
- Iron and copper concentrations and loads reduced from Copperas Brook to WBOR
    - 99% reduction in Cu concentration
        - > 90% reduction just below South Mine and just below South Open Cut
    - 95% reduction in Fe concentration
- 4-unit pH shift
- Continued decline in leachate flow
    - 54 gpm reduced to 11 gpm

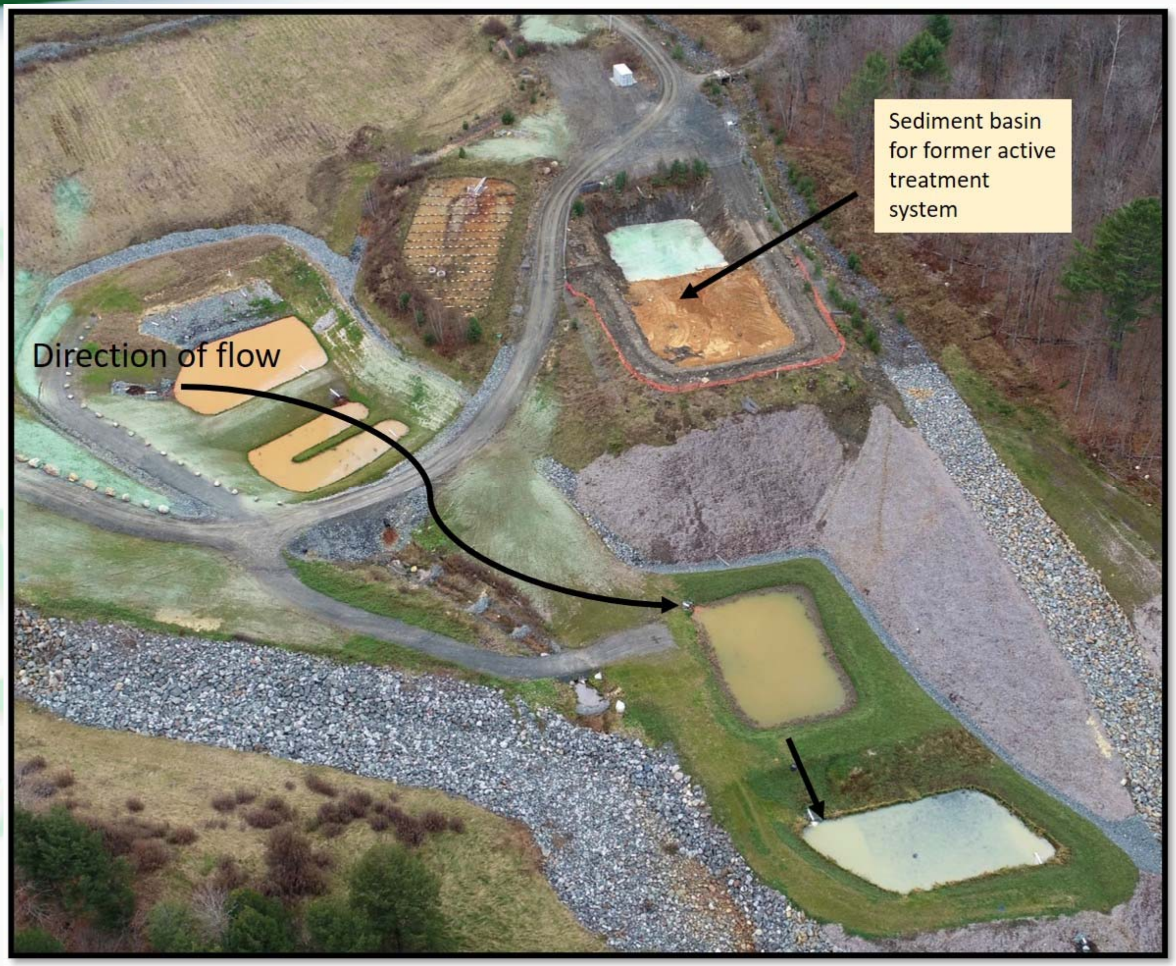


Final Remarks – Notable Success

- West Branch of the Ompompanoosuc River was removed from the federal impaired waters list in 2014
  - The treatment system, along with other site cleanup activities has resulted in the West Branch of the Ompompanoosuc River to achieve the Vermont water quality standards for the 1st time since monitoring began in the 1960’s, and likely since the early 1800’s.

Final Remarks – Long-Term Leachate Treatment

- With all actions completed at the site, a passive treatment system became viable as a long-term strategy
  - Installed and became operational in summer 2019
  - Performance of the passive treatment system will be a subject of a future webinar



Sources Cited Within Slides

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Thank you! Questions?

EPA Report available

Butler, Barbara A. and Hathaway, Ed, 2020, Evaluation of Rotating Cylinder Treatment System at Elizabeth Mine, Vermont. EPA 600-R-19-194.