The Evolving Role of Constructed Wetlands in Remedial Wastewater Treatment – A 25 Year Perspective

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Origins of Constructed Wetland Treatment

- General category of “passive” water treatment
- Uses natural contaminant removal processes with little or no external power or reagent feeds
- Developed in 1980s for abandoned mine drainage (AMD) and coal combustion residual (CCR) leachate
- Based on observations that water quality improved passing through natural wetlands
- Early designs focused on replicating natural vegetated systems
Vegetated wetlands provide a variety of functions for contaminant removal

Many different Eh–pH environments may be present

Natural swamps originally trapped contaminants in coal

Constructed wetland treatment seeks to replicate ore formation processes
Vegetated wetlands are not always effective for parameters with narrow Eh–pH removal ranges (Se, Mn, ...).
Greater control needed for Eh–pH conditions

Research in 1990s isolated wetland treatment functions in targeted Eh–pH components

PERT design approach sequences components in preferred natural order of ore deposition

Allows more efficient sizing of components by predicting the discharge quality from each in sequence
Basic PERT Design Components

- Vertical Flow Limestone Beds (VLBs)
  - Downflow beds of limestone to remove acidity

- Oxidation/Precipitation Basins (OPBs)
  - Settling basins with influent aeration

- Surface Flow Wetlands (SFWs)
  - Aerobic vegetated wetlands for metals removal

- Organic Reduction Cells (ORCs)
  - Downflow organic beds with strongly reducing conditions

- Subsurface Flow Wetlands (SBWs)
  - Vegetated wetlands with porous substrates for solids removal

- Manganese–Oxidizing Beds (MOBs)
  - Aerobic gravel beds colonizing Mn–oxidizing bacterial
General Eh–pH Ranges for PERT Components

The diagram illustrates the general Eh–pH ranges for PERT components, showing the oxidation states of selenium (Se) and the pH sensitivity of different species. The diagram highlights the range of selenium immobility and different oxidation states of Se, such as Se⁰, H₂SeO₃, HSeO₃⁻, SeO₄²⁻, SeO₃⁻, and Se²⁻. The graph also indicates the upper and lower limits of water stability, with areas shaded to represent different water states: oxidized (Water Oxidized) and reduced (Water Reduced). The diagram is used to understand the environmental conditions under which different selenium species become more or less mobile.
PERT Treatment Approach

Passive Treatment Components

**VLBs**
Vertical Flow Limestone Beds (VLBs)
Primary neutralization of acidity, increase of pH

**OPBs**
Oxidation/Precipitation Basins (OPBs)
Primary removal for major sludge-formers

**SFWs**
Surface Flow Wetlands (SFWs)
Removal of remaining sludge-formers and oxidizable elements

**ORCs**
Organic Reduction Cells (ORCs)
Removal of trace elements in reducing conditions

**SBWs**
Subsurface Flow Wetlands (SBWs)
Removal of remaining solids and organic compounds from VFCs

**MOBs**
Manganese-Oxidizing Beds (MOBs)
Removal of manganese and related trace metals

Acid Fe As* Al Se Hg Cr TSS Mn

*Also Be, Sb

Other Potential VFC Elements: Cd Pb Cu Tl Ni Zn
Constructed Wetland System Evolution
1987 – 2011

- Number of Passive Technologies
- Number of System Components
Albright System 1987

- CCR leachate and AMD
- Treating for pH, Fe, Mn
- “Free-form” wetland cell designs in 1987
- New SFW cells added in 1992 to improve Mn removal
- MOBs added in 1996 for final compliance
Springdale System 1995

- CCR leachate and AMD
- Treating for pH, Al, As, B, Fe, Mn, Se, TSS
- Research and compliance project with EPRI
- Tested multiple technologies together
- Multiple award winner – formed basis of PERT
Hatfield System 2000

- CCR leachate and AMD
- Treating for pH, Al, As, Fe, Mn, Tl, TSS
- First full PERT application
- SFW cells used for polishing rather than primary Fe treatment
- Refined MOB sizing criteria, regular cell outlines
Harrison System 2003

- CCR leachate and AMD
- Treating for pH, Al, As, Cr$^{6+}$, Fe, Mn, Se, TSS
- First use of ORCs for Cr$^{6+}$ and Se
- Secondary SFWs used for solids control
Flue gas desulfurization (FGD) wastewater
Treating primarily for As, Fe, Hg, Se
Pre-existing SFWs had poor Se removal
3 SFWs replaced with 6 ORCs
Greatly enhanced Se & Hg removal
Long-Term Performance
Selenium – Harrison

Selenium (μg/L)

Influent
Effluent

Year
System Component Performance
Selenium – Harrison

Selenium (mg/L)

Component Discharge
Regulatory Limit

Influent  OPB1  OPB2  SFW1  SFW2  SFW3  ORCs  SFW4  Effluent

0  20  40  60  80  100  120

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Future Considerations

- Vegetated wetlands will remain a key component of passive treatment systems
- Proposed EPA utility wastewater guidelines recognize biological treatment as a compliance option
- Biological systems are a low–cost, sustainable solution for wastewater remediation on remote and unstaffed sites
- Exclusion of wildlife may become a consideration for future designs
Wetland of the Future?
Questions & Discussion
Vertical Flow Limestone Beds (VLBs)

- Used for acidity removal
- Basal limestone bed with top cover of organic compost
- Generate alkalinity from limestone and sulfate reduction
- Also remove Fe and Al, but this can cause clogging
Oxidation/Precipitation Basins (OPBs)

- Used for aerobic precipitation of metals and sludge storage
- Deep open water basins, usually with 24+ hours detention
- Aeration provided at inlet
- Work well for Fe and Al, also remove As with Fe co-precipitation
Surface & Subsurface Flow Wetlands (SFWs, SBWs)

- Effective for polishing many parameters
- Contain aerobic and anaerobic components
- Blended organic substrate and shallow water for SFWs
- Porous substrate for SBWs
- Work best for residual Fe, Al, and solids (TSS) removal
Organic Reduction Cells (ORCs)

- Similar to VFWs, but with a thick top organic bed
- Create strongly reducing conditions
- Effective for Se, Hg, Cr$^{6+}$, and others mobile in oxidizing conditions
- Should be followed by SFWs or SBWs for solids polishing
Manganese-Oxidizing Beds (MOBs)

- Shallow basins filled with 1 – 2 feet of gravel
- Create growth surface for manganese-oxidizing bacteria
- Mn deposited as pyrolusite ($\text{MnO}_2$)
- Require low influent Fe – placed at end of system