PROCESS SELECTION & DESIGN OF A PASSIVE TREATMENT SYSTEM FOR THE EMPIRE MINE STATE HISTORIC PARK, CALIFORNIA[1]

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Abstract. The Empire Mine State Historic Park near Grass Valley, California offers the ever-curious public a unique step back in time by preserving the underground mining heritage of the western slope of the Sierra Nevada. Perennial flow of a neutral pH, mining influenced water containing iron, arsenic, manganese, and other trace metals through the Magenta Drain adit is an unfortunate legacy of that heritage. Peak Magenta Drain flows requiring treatment are expected to be 4,740 L/min (1,200 gallons per minute). Several active treatment options were evaluated, including traditional lime dosing and green sand; alternative passive treatment technologies, including biochemical reactors, were also considered. However, bench scale test results suggested that simple settling of suspended iron oxy-hydroxide (with co-precipitated arsenic) and passive aerobic precipitation of manganese oxide could satisfy discharge targets.

Land area in the vicinity of the Magenta Drain portal was inadequate to site the passive treatment system in a manner that would allow gravity flow. Land was available, however, near the crest of a nearby ridge. Consequently, the design included an influent pumping system, overland pipelines, settling pond, and two styles of aerobic wetlands. Once the decision to embrace a passive treatment system concept based on life-cycle cost and appropriateness for a public historic park was made, design plans and specifications were developed on a fast-track basis. The paper summarizes the rationale for the selection of passive treatment and provides design details that include trace metal removal in an aerobic environment.

Additional Key Words: mining influenced water, arsenic, manganese, trace metals

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Introduction

The California Department of Parks and Recreation (DPR) operates the Empire Mine State Historic Park which is located near Grass Valley, California, about 80 km (50 miles) northeast of Sacramento, the state capitol. The typical elevation of the site is 800 m (2624 ft); it is heavily forested with many mature trees with trunk diameters exceeding 1.02m (40 inches). See Fig. 1.

Figure 1. Site Location

According to information available from www.empiremine.org (2011), the Empire Mine is the site of the oldest, largest, and richest gold (Au) mine in California. From 1850 to its closing in 1956, it produced about 170,000 kg (5.8 million ounces) of Au. The park contains many of the original mine buildings, the owners' cottage, and the restored gardens and grounds. There are about 592 km (367 miles) of underground mine workings situated beneath the 342 ha (845 acres) of hiking trail laced, wooded parkland. Most of the underground mine workings are flooded, comprising one massive mine pool with an identified underground "spill point" that contributes in maintaining a relatively constant mine pool surface elevation. The Magneta Drain is a drainage adit that is connected to the mine workings and it discharges net neutral pH mining influenced water (MIW) with dissolved concentrations of Fe, As, and Mn. Trace amounts of secondary contaminants including Al, Sb, Ba, Cd, Cr, Co, Cu, Pb, Hg, Ni, Th, V, and Zn have also been detected in water samples.

Observations suggest that the flow in the Magenta Drain is directly influenced by local rainfall, which infiltrates into the mine pool proper and into mine workings down gradient of the underground spill point, producing a fairly quick flow response to surface water events.

The main project goal is to provide the DPR with a cost-effective treatment sytem whose effluent would comply with the requirements prescribed in the Regional Water Quality Control Board (RWQCB) Waste Discharge Requirements order and the effluent limitations prescribed in a National Pollutant Discharge Elimination System (NPDES) permit. The paper summarizes the rationale for the selection of passive treatment as the preferred remediation alternative and provides design details that address trace metal removal in an aerobic environment.

Treatment Process Selection History

The initial intent was to design a gravity-fed, totally passive treatment system (PTS) to treat the Magenta Drain effluent. However, early assessments assuming a treatment capacity of only 3.03 m^3/min (800 gpm) revealed that there was insufficient land area within the park boundary to allow the 100% gravity-fed PTS design approach. Subsequent design efforts revealed that even a full-scale lime dosing active treatment system would not fit within the park boundary adjacent to the Magenta Drain portal; the drain discharge would still need to be pumped to a more-suitable site uphill. The treated effluent would flow back to the channel that historically received the Magenta Drain discharge. The projected life cycle cost, including capital and operating cost for 100 years, was projected to be $35 million (2009 dollars). This process entailed a significant carbon footprint of 8,710 metric tons of CO_2 over 100 years and the treatment facilities would have adverse visual (e.g., buildings displacing natural parkland habitat and hiking trails) and noise impacts (e.g., chemical supply trucks, sludge handling vehicles) if implemented. The findings prompted a re-examination of the “green technology” passive treatment option with a dedicated pump station whose comparative 100-year life cycle cost was only $6.2 million and 20% of the carbon footprint estimated for the active treatment system with the same capacity.

The final design included a PTS composed of:

- a water collection structure and pump station
- overland and partially buried conveyance piping
- passive treatment components (settling pond and a multi-celled free water surface wetland)
- associated infrastructure (vehicle access and utilities).

Figure 2 shows approximate locations and relative sizes of the PTS components. Essentially, the effluent MIW from the Magenta Drain at or near the current portal location will be collected and pumped through conveyance piping heading southward, up-hill, on DPR property to the area near the top of the drainage by East Empire St., a main access road. Here, the passive treatment components (settling pond and wetlands) will be placed to create a gravity flow system to bring the water through the pond and wetlands and back down-hill, northward, through conveyance piping to the existing stream just downstream of the collection structure. Utilities and vehicle access will be provided for the pumping station. Construction commenced in April, 2011.

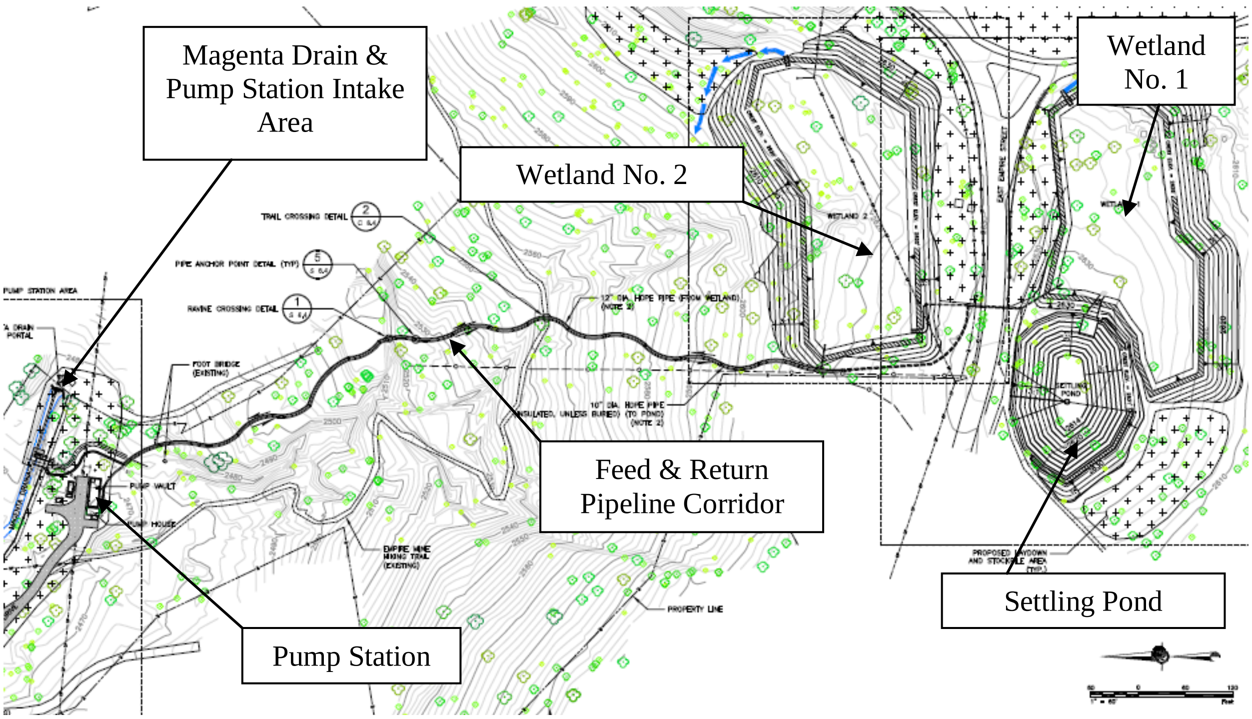

Figure 2. Site Layout Plan.

Design MIW Flow Rates and Expected Chemistry

Treatment Goals

The NPDES permit contains effluent limits for total suspended solids, settleable solids, pH, turbidity, color, Al, Sb, As, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Ni, Th, V, and Zn. All of the metal effluent limits are for the total recoverable fraction. Total and total recoverable concentrations are considered to be equivalent and the terms are used interchangeably in the paper.

The Magenta Drain effluent currently flows through an open channel for about 500 m (1,600 ft), most of it through a public park, before it disappears into a culvert and joins the flow in nearby Wolf Creek. The invert of the channel is covered with Fe precipitates that have deposited since the Magenta Drain adit was completed in the 19th century. The channel behaves somewhat like a constructed wetland; however, the characteristics of the precipitates necessitated the placement of a security fence on the banks of the channel through the park to restrict public access. The completion of the project should allow the final removal of the precipitates and the security fence, and restoration of the channel to a more natural appearance.

Influent Water Quality

The Magenta Drain portal had been sampled on a monthly basis since 2006 by DPR and MFG, Inc. Golder Associates Inc. (Golder) also monitored the Magenta Drain portal chemistry during a bench scale test of the PTS design concept. In the final design, summary data from the monitoring events and the Golder bench test were considered. The data indicated the following:

- Exceedances of the effluent limits for color, turbidity, As, Fe and Mn were frequent, occurring in the majority of the samples; and
- There were scattered exceedances of the effluent limits for Al, Cu, Pb, Th and Zn.

Previous treatment efforts (MFG, 2008) focused on As, Fe and Mn as constituents of concern (COC). Consideration of other potential metals was included in the PTS design with the intentional removal of Mn. Moreover, removal of the three primary constituents to permit limit values should also result in compliance with the color and turbidity limits as well as secondary contaminants.

Table 1 summarizes measured influent values from Golder passive treatment bench testing and DPR/MFG sampling from 2nd quarter 2006 through 4th quarter of 2007.

Table 1. Passive treatment influent MIW design concentrations

Parameter	Design Concentration, mg/L	
	Golder Bench Testing	DPR/MFG Data
Arsenic, total	0.13	0.119
Iron, total	24.0	10.5
Manganese, total	3.2	3.52

Review of Passive Technologies with Bench Testing

In 2008, four different passive treatment technologies were evaluated during an on-site bench test: biochemical reactor (BCR), ChitoRem™, zero valent iron (ZVI), and an aerobic wetland (Fig. 3). During the bench test, influent water quality was typically consistent with historic data from the Magenta drain. However, the concentrations of the primary COCs, (Fe, As, Mn) varied significantly during the test. Total As concentrations were below the effluent limits for the first four weeks of the study, indicating that this COC may not violate the effluent limits for potentially significant, low-flow periods, of the year. Cadmium was the only other parameter, or secondary COC, to exceed the effluent limit in the Magenta Drain water during the bench testing.

A summary of the performance of the four test systems follows.

- BCR cell – The BCR cell successfully reduced total As to levels below the effluent limit. However, the BCR did not reduce total Mn or total Fe below the effluent limits. The BCR cell also leached As, Fe, and Mn over the course of the first month.
- ChitoRem™ cell – The ChitoRem™ performed similarly to the BCR cell and successfully reduced total As to levels below the effluent limit. However, the ChitoRem™ did not reduce total Mn or total Fe to below the effluent limits. The ChitoRem™ did achieve the highest level of total Mn removal, averaging 86% removal during the high period. The ChitoRem™ cell also leached As, Fe, and Mn over the course of the first month.
- ZVI cell - The ZVI cell successfully removed total As to levels below the effluent limit but did not remove Mn or Fe successfully. The operational issues with the ZVI cell (partial plugging) were grounds for eliminating this technology from further consideration at the site.
- Wetland cell – The wetland cell successfully removed total As and total Fe to levels below the effluent limits. Although the wetland cell did reduce total Mn concentrations significantly (67% removal), the effluent concentrations still remained approximately one order of magnitude greater than the effluent limit.

The wetland and ZVI cell feed waters were pre-treated in the bench settling pond. The settling pond did achieve approximately 60% total As removal and 66% total Fe removal, indicating that a significant portion of the total As and Fe could be removed via settling alone.

The bench performance data supported the concept of an aerobic wetland PTS and this treatment process was selected as the preferred alternative. Additional data regarding this test follows.

- The bench wetland removal rate for Mn was 67%, but it did not meet the effluent limit of 50 µg/L, probably due to system immaturity.
- Significant amounts of total As and Fe were removed in the settling pond. All future treatment efforts on site would include a pre-treatment settling pond with a minimum retention time of 12 hours.
- System retention times were determined during the bench testing. For As treatment, the recommended hydraulic retention time in the wetland cell was about three hours.
- The average total Fe removal rate from the bench wetland was 7 g/d/m^2; the average total Mn removal rate was 0.9 g/d/m^2. These removal rates served as the design basis for the treatment designs at the site.
- Aside from the primary COCs, Cd was the only other parameter to exceed the effluent limit in the Magenta Drain water. The wetland cell was the only process to remove Cd without leaching other metals.

Figure 3. Initial (left) and 10-week-old (right) bench test wetland cells

Design Flow Rate

While pumping from the mine pool was technically feasible, conventional wisdom supported the concept that it was better to maintain a constant mine pool elevation and avoid wide fluctuations from direct pumping. Thus, MIW collection and pumping would occur at the Magenta Drain portal; site hydrologic data supported a peak design flow rate of 4.7 m^3/min (1,200 gallons per minute). This is the projected flow peak for a 25-year recurrence interval.

A pump station at the Magenta Drain portal will deliver MIW via insulated pipeline to the settling pond. The design for this aspect of the PTS is outside the focus of this paper but the pump station will be fitted with four pumps, each capable of pumping 1.6 m^3/min. (400 gpm); the fourth pump was included in the design as a rotating spare. In case of a power outage, a backup generator was included in the design.

The annual operating cost for the pumping component of the PTS (electricity) is about $9,000. The annual labor (including fringe benefits) to operate the PTS is estimated to be about $20,000. The operating costs would be funded under the Empire Mine State Historic Park budget.

Passive Treatment System Design

The proposed passive treatment system will consist of a settling pond and aerobic wetlands, fed by the Magenta Drain portal pump house. The design was based on the results of the bench study (Golder, 2009). Background information regarding that study follows.

Metal Removal Kinetics

Aerobic wetlands (wetlands) are engineered treatment systems that are designed to mimic the treatment processes that occur in naturally-occurring wetlands. Aerobic wetlands can treat a variety of constituents including suspended solids and metals (Kadlec and Knight 1996). If appropriately sized, aerobic wetlands can remove Fe and Mn via iron hydroxide and Mn oxide precipitation, respectively. Metals removal from wetlands is typically calculated as a mass area loading factor with units of grams per day per square meter ($g/d/m^2$) whose origin is described below. Some technical references cite this value in units of grams per square meter per day ($g/m^2/d$) or gdm.

Iron

Typical Fe removal rates vary from 10 to 20 $g/d/m^2$ (Hedin et al. 1994). A typical Mn removal rate of 0.5 to 1 $g/d/m^2$ was reported by Hedin et al. in 1994 but subsequent observations by others suggest that these values are conservative. Aerobic wetlands do not require chemical inputs or significant maintenance. One potential disadvantage of aerobic wetlands can be the large amount of land required for effective treatment.

MIW wetland research during the 1980s focused on cattail-dominated systems involving Fe and Mn removal at coal mining sites. While working for the former U.S. Bureau of Mines, Bob Hedin and Bob Nairn developed the concept of measuring aerobic wetland cell performance by using mass balance accounting in about 1992 (Hedin 2002). They noticed distinct performance differences in aerobic cells treating net acidic and net alkaline MIW containing Fe and Mn. They further developed empirical mass loading/removal factors (mass load in – mass load out = net removed) per unit surface area for Fe and Mn. These are typically reported as "gdm" factors for grams per day per square meter of wetland water surface.

This data approach was used in the Magenta Drain bench study which developed site-specific gdm factors for Fe and Mn.

Arsenic

The kinetics of adsorption of As on to iron oxyhydroxide are not fully understood but have been documented in the literature (Leblanc et al. 1996). Langmuir et al. (1999) suggest that a Fe/As molar ratio of at least 3:1 to 5:1 is required to provide acceptable sequestration of As to Fe precipitates. The ratio of Fe to As in the Magenta Drain MIW has a ratio of 88:1 (DPR and MFG data) to 184:1 (Golder bench test data). It would appear that as long as Fe is being removed in the PTS, that As would report with it. This was indeed found to be the case in the bench testing.

Manganese

The technical literature abounds with references, some written over 25 years ago (e.g., Bender et al. 1994), that document how Mn is removed in aerobic passive treatment systems biogenically. Robbins and Ziemkiewicz (1999) observed the presence of 12 different biological mechanisms removing Mn in a passive treatment system at the Shade coal mine which was constructed in the early 1990s (Brant and Ziemkiewicz 1997). At this site, influent Mn concentrations were reported reduced from 12 to 25 mg/L down to less than 2 mg/L. Manganese removal kinetics from MIW has been empirically measured in a way similar to Fe as developed by Hedin (1994). Hedin observed typical Mn removal rates ranging from 0.5 to

1 g/d/m^2 but there may have been interfering conditions that were unrecognized at the time. More recent data suggest that higher values are possible.

Rose et al. 2003 discussed two Mn removal methods, a limestone bed where MIW passes through granular limestone in a plug-flow configuration and an open limestone channel configuration with a free-water surface above a bed of granular limestone. Key findings in the paper include:

Effective Mn removal [in both bed and channel configurations] requires oxidizing well-aerated water, as well as prior removal of essentially all dissolved Fe and Al, and pH above about 6.5.

Another key requirement for Mn oxidation is a low concentration of ferrous iron (Fe^{2+}). …if Fe^{2+} is present in a solution…, the oxidation potential of such a solution is considerably below the level required for Mn oxidation to Mn(III) or Mn(IV), and Mn will not oxidize and precipitate.

Several of the [bed] systems have failed because of plugging of the inlet area with silt, leaves, Fe and/or Al precipitate, grass and other materials.

Most Mn removal rates [in limestone beds] range from 1.5 to 5 g/m^2/day, with the lower values from beds with influents containing appreciable Fe and Al.
Three successful limestone-lined channels have been observed, one with a Mn removal rate of about 10 g/m^2/day. A shallow bed or channel, lined with limestone, and containing algae to enhance O_2, appears to be an improved design.

Data reported by ITRC (2010) cite a Mn removal rate of 2.6 g/d/m^2 at an abandoned coal mine site in Alabama.

Based on the findings of Rose et al. 2003, an open channel, lined with limestone was selected to be the best configuration for Mn removal. This is consistent with the bench test configuration which did not include limestone or any special algae inoculation other than that which appeared to have been present naturally with the locally-purchased wetland plants. See the comparative photos in Fig. 3, especially the middle (open water) zone which appeared to have accumulated an algal mat during the course of the 12-week experiment.

Secondary Contaminants of Concern (Cu, Cd, Zn, Pb, Tl)

Secondary COCs in the MIW are likely to adsorb to manganese oxides that should form in the wetland zone of the PTS. Review of the technical literature on this topic verified that manganese oxide minerals should indeed be capable of removing the secondary COCs in the Magenta Drain MIW. For example, the following direct citation from Tebo et al. (2004) is offered:

> *Mn oxide minerals can adsorb or incorporate substantial amounts of **Cu**, Co, **Cd**, **Zn**, Ni, Sn, **Pb**, Ca, Fe, Ra, Hg, U, Pu, Po, As, Se, and Th (see multiple references in Tebo et al. 2004). These interactions have been reported to decrease dissolved trace metal and radionuclide concentrations by orders of magnitude (see multiple references in Tebo et al. 2004) even when only small amounts of Mn oxides are present (see Jenne 1968 cited in Tebo et al. 2004).*

For emphasis, the secondary COCs in the Magenta Drain MIW are **bold** in the citation above. It is unclear if Th would be removed by adsorption to manganese oxides or immobilized in reducing (deeper) zones of the wetland cells. The reported efficiency of removal of mercury (Hg) and lead (Pb) by manganese oxides suggests that Th (which is positioned between these two elements on the periodic table) might also be removed by adsorption mechanism, but it has never been documented.

Removal kinetics for the secondary COCs in the Mn removal portion of the PTS are unknown. However, this information may become available as the PTS matures.

Settling Pond Design

The preliminary sizes of the settling pond and wetlands in the Magenta Drain PTS were estimated using the public-domain software: AMDTreat. See http://amd.osmre.gov.

The primary settling pond capacity was sized to provide twelve hours of storage for a pumped design peak flow of 4.7 m^3/min (1,200 gpm). The design included storage volume for 1,144m^3 (1,496 yd^3) of iron oxyhydroxide precipitate. The water volume of 3,271m^3 (864,000 gal) is necessary to provide 12 hours of retention: 1,200 gal/min times 720 minutes = 864,000 gal.

The Fe precipitate volume was determined with AMDTreat assuming:

- a precipitate density of 8.35 lb/gal (1.0028 kg/L) (based on experience)
- 5 percent solids (based on experience)
- 1,136 L/min (300 gpm) “typical” flow (this is somewhat conservative, as the typical flow could be as low as 871 L/min (230 gpm))
- Iron concentration of 24 mg/L (this too, is conservative, because the expected Fe concentration in the settling pond effluent is 5 mg/L, yielding a net deposition of only 19 mg/L of Fe in the pond as settled solids)
- The settling pond is cleaned out once every 4 years (0.25 times per year) – the actual cleaning frequency may be different.

The settling pond will be formed by earthen cells lined with a geosynthetic membrane. The influent feed water will report to a floating curtain well positioned at the deep end of the settling pond to mimic the behavior in a typical sludge thickener. A leak detection system was not deemed required because any leaks would be captured through percolation back into the Empire Mine mine pool and the leakage would be expected to be of better quality than the mine pool itself. This aspect of the design was developed more fully for the RWQCB. The spacial relationship between the proposed PTS and underground workings is shown in Fig. 4.

The settling pond overflow will be comprised of a combination weir that attenuates flow pulses during normal pump cycling at less than peak MIW delivery rates. Sediment accumulation in the settling pond would be manually sounded periodically from a dedicated flotation unit such as a small fiberglass rowboat.

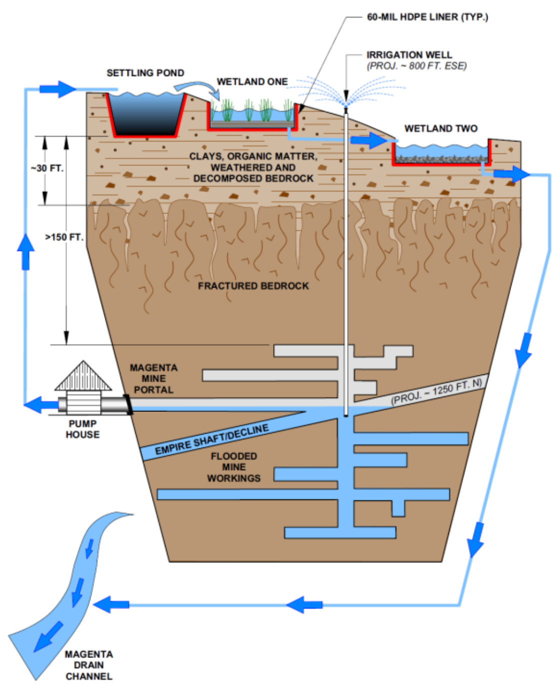

Figure 4. Schematic cross section of the PTS and the Empire Mine

Wetland Sizing

The wetland portion of the Magenta Drain PTS was based on:

- the design flow of 4.7 m^3/min (1,200 gpm),
- an influent Fe concentration of 5 mg/L
- an "influent" Mn concentration of 0.5 mg/L (the actual value is 3 mg/L, but space restrictions at the steeply sloped site only allow room to remove about 0.5 mg/L)
- Fe removal rate of 7 grams per square meter per day (bench test data)
- Mn removal rate of 0.9 grams per square meter per day (bench test data)
- 15 cm (6 inches) of standing water depth
- 30 cm (12 inches) of wetland soil (combination of soil and limestone rock)
- 60 cm (2 feet) of freeboard
- interior concrete walls to control short circuiting
- 3H:1V side slopes

The total wetland water surface area necessary was estimated to be 8,308 m^2 (89,400 sq ft). This approximate amount was allocated between Wetland Number 1 (on the south side of Empire Street) and Wetland Number 2 (on the north side of Empire Street) by trial and fit with the goal of minimizing the size of Wetland 2 to help control costs. The terrain on the north side of Empire Street has steep slopes, requiring a significant amount of cut and fill. It is interesting to note that a natural wetland may have been present near the proposed Wetland 2 site; it had been altered by historic mining activity.

The actual design total wetland water surface is about 8,225 m^2 (88,500 sq ft) when the interior concrete walls are considered. This is 99% of the required value cited above and within the margin of uncertainty of the kinetic metal removal rates which are considered conservative.

Actual surface water area allocations between Wetland 1 and Wetland 2 follow.

Wetland 1

The Wetland 1 surface water allocation was 3,864 m^2 (41,581 sq ft). At 4.7 m^3/min (1,200 gpm), this unit of the PTS will be completely dedicated to Fe removal at an estimated rate of 7 gdm^2. Little, if any, Mn removal is expected during design flow events. However, Mn removal is likely to occur during "typical" flow of about 0.9 m^3/min (230 gpm). As suggested above, an interior concrete wall 76.2 cm (30 inches) high (from top of the liner) will be constructed through the cell to minimize “dead spots” in the surface water flow regime. In essence, the clarified water from the settling pond will:

- flow through a circuitous willow-planted zone to encourage oxidation and then
- return toward the west to the cell outfall, where
- a drop spillway will be connected to
- a gravity-flow pipe beneath Empire Street that
- daylights at the feed end of Wetland 2 on the north side of Empire Street

This gravity flow pipe will share a culvert with the influent pipeline from the pump station. The culvert ends will be sealed off plugs which will be covered with soil. This would allow access to the pipes in the future without needing to excavate across Empire Street.

At the peak design flow, a flow depth of 15 cm (0.5 ft), a “channel width” of 9.2 to 18.3 m (30 to 60 ft), and an assumed Manning’s N value of 0.045, the channel slope is nearly flat through Wetland 1. The floor of the cell will be completely planted with containerized willow plants as subsequently discussed.

To allow operational flexibility, several gaps will be installed in the concrete wall and filled with removable blocks. This will also allow partial periodic by-passing of flow to Wetland 2 to sustain algae growth.

Wetland Number 2

The Wetland 2 surface water allocation was 4,522 m^2 (48,658 sq ft). At the design peak flow, this unit of the PTS will be only partially dedicated to Fe removal at a rate of 7 gdm^2 and mostly to Mn removal at a rate of 0.9 gdm^2. Again, to minimize “dead spots” in the surface water flow regime, an interior concrete wall 76 cm (30 in) high will be installed along the long axis of the cell. It too will be fitted with gaps filled with removable blocks. The influent from Wetland 1 will flow east, parallel to a centerline concrete wall and return toward the west to the cell outfall, which will be a drop spillway connected to a gravity flow pipe. This pipe will be connected to the system outfall and energy dissipater structure near the pump station.

As with Wetland 1, the channel slope is also nearly flat through Wetland 2. The floor of the cell will not receive containerized willow plants as discussed below.

At the peak design flow, very little of this unit of the PTS will be dedicated to Fe removal because most, if not all of the Fe will have been removed in prior PTS components (i.e., the Settling Pond and Wetland 1). No willows will be planted. The floor and side slopes will be covered with a 7.6 cm (3-in) layer of crushed limestone to encourage biological Mn deposition.

Wetland Hydraulics

Wetland 1 effluent will enter an upturned pipe spillway equipped with a trash rack and be conveyed by gravity through a buried pipe beneath East Empire St. The water will enter the feed end of Wetland 2 via a cascade channel to improve oxygenation of the water. The outfall from Wetland 2 will be similar to Wetland 1: a drop pipe arrangement with a trash rack. Both wetland cells will be fitted with emergency, open channel spillways that discharge into natural drainages in extraordinary storm events or upset conditions. This safety feature allows a somewhat controlled release of water during upset conditions without human intervention.

Wetland Soils and Media

The floors of Wetland 1 will be covered by 30 cm (12 in) of soil to provide a rooting medium for the plants described below. This soil will be comprised of the topsoil that will be excavated in the clearing and grubbing activities for the settling pond and the wetlands. If the volume of topsoil is not sufficient, additional volume may be manufactured on-site using commercially-available compost and other organic media.

In Wetland 2, only about 23 cm (9 in) of soil will be placed on the floor of the cell and the interior side slopes. The upper 7.6 cm (3 in) will be comprised of a layer of crushed limestone to provide a medium conducive to manganese oxide deposition. This design feature was prompted by the findings presented in Rose et al. 2003. As with Wetland 1, the interior slopes of Wetland 2 will be covered with limestone rock armor.

The limestone rock particle size will be 2.5 to 5 cm (1 to 2 in) in nominal diameter to facilitate coating with manganese oxide. The calcium carbonate content is not particularly important, so a slightly out-of-spec limestone product would be acceptable.

Numerous researchers (e.g., Brant and Ziemkiewicz, 1997) cite the advantages of rapidly establishing a cyanobacteria (algae) community in advancing the maturity in Mn removal zones of wetlands. This approach could potentially encroach on patent issues, so it will not be implemented. Wetland 2 is expected to “self inoculate” with indigenous manganese-oxidizing microbes that should already be present in the Magenta Drain effluent. This occurred in the 12-week long bench study and is expected to be replicated once the PTS is commissioned.

Wetland Vegetation

A study of two supposedly identical biochemical reactors at the Haile Mine in South Carolina (Gusek, 2010) suggests that willows are somewhat better than other wetland species in oxygenating water. This was confirmed independently in the literature.

Ten hydrophilic species, ranging from willows, rushes, sedges, cattail, and lily, were identified in the Sand Dam Marsh, a volunteer wetland habitat within the park.

Undoubtedly, some of these species will naturally invade Wetlands 1 and 2 over time if they can out-compete the species initially planted. However, due to the oxygenating ability of the willows (*salix*), and their ability to be installed as plugs (propagated from cuttings harvested from the Sand Dam Marsh on site) in the wetland soils, they will be the predominant plant encouraged to grow in the non-limestone portion of wetland zone of the PTS. This is essentially all of Wetland 1; willows will not be planted in Wetland 2.

Flow Measurements

Several instrumentation features have been included in the design to document flow rates. A self-powered propeller type flow meter will be used on the pumped water to indicate the influent flow rate and record total volume fed to the treatment system. Two H-flumes will be used to measure flow in the gravity fed part of the system. One will be installed at the discharge end of the gravity return flow pipeline that records flow information to a data logger. The other flume will be located between the two wetlands to gage flow at the process “mid-point”; it will be fitted with a battery-powered data logger. The flow data will be used to determine conditions related to intentional by-passing or to estimate losses/gains from evapotranspiration or precipitation events.

Expected Effluent Water Quality

The effluent water from the PTS should consistently meet the discharge limits for Fe and As. It is unclear whether it will achieve the Mn discharge standard on a continuous basis. It should be able to meet the annual average discharge criteria agreed upon with the RWQCB for Mn. The design was conservatively based on the bench scale results of 0.9 grams of Mn removal per day per square meter of water surface area. However, data in the public domain suggest Mn removal kinetics ranging from 2.6 gdm^2 (ITRC, 2010) to 10 gdm^2 (Rose and Ziemkiewicz, 2003). It is likely that the bench test Mn kinetics would have improved if the bench test period was extended; data in Brant and Ziemkiewicz (1997) suggest that at least eight weeks of operation was required to first observe black manganese oxide coatings on limestone at the Shade, PA site.

It is appropriate to discuss the expected influent and effluent characteristics for each of the components of the Magenta Drain PTS because the sizing of the components depends on the efficiency of the previous component in the treatment train.

Figure 5 below provides expected water chemistry with respect to Fe and Mn at different expected flow rates. This chart is based on a simple mass balance model that predicts effluent concentrations assuming that the kinetic removal rate in each cell is realized.

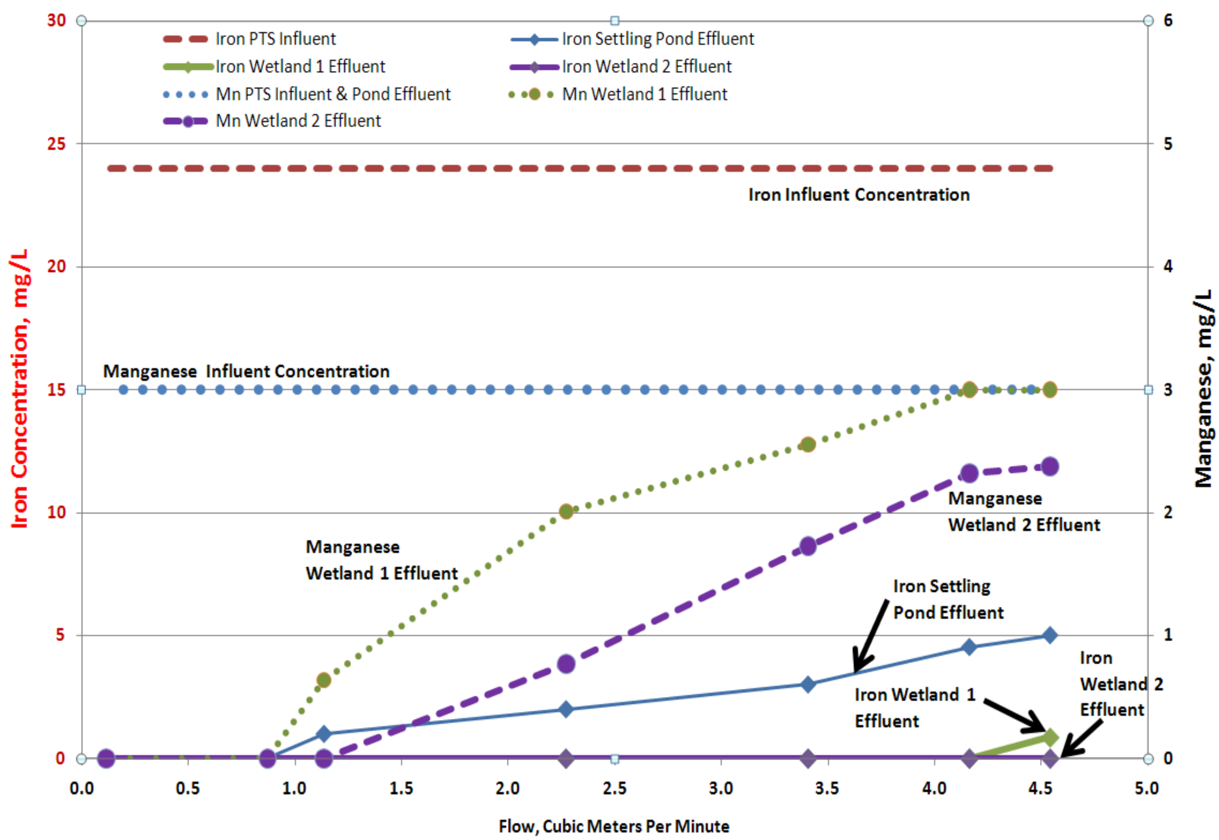

Figure 5. Expected MIW chemistry at various locations and flow rates

Detailed discussions for each major component of the system follow.

Expected Settling Pond Effluent Quality

The assumed settling pond influent quality is provided in Table 2. Based on the bench study, it is assumed that the effluent quality (at full design flow) will contain 5 mg/L of Fe, and 3 mg/L of Mn. At lower than design flows, the concentrations of Fe may be less, but to what extent is unknown.

For the purposes of the model, the following values were assumed and/or estimated:

Table 2. Estimated Settling Pond Effluent Quality at Various Flow Rates

Flow m^3/min (gpm)	Estimated Effluent Fe (mg/L)	Hydraulic Retention Time (Hours)
4.54 (1200)	5	12
4.16 (1100)	4.5	13
3.41 (900)	3	16
2.27 (600)	2	24
1.14 (300)	1	48
0.87 (230)	0.0005	63
0.11 (30)	0.00005	480

Table 2 Note: Only the 12 Hr HRT effluent value has been based on actual bench test results; low values are assumed to be zero but need to be a positive value to avoid division by zero in the model.

Expected Aerobic Wetland 1 Effluent Water Quality

Note that at the typical flow rate of 0.9 m^3/min (230 gpm), virtually all the Fe is removed in the settling pond. It is assumed that no Mn removal occurs in the settling pond at any assumed flow rate. The hydraulic retention time in Wetland 1 at all flow rates is about 4.3 hours due to the direct relationship between flow rate and flow depth in the wide channel with a very flat bed slope.

The recommended retention time for As removal from the bench test was 3 hours. This criterion is met by the current Wetland 1 design.

The mass balance model results suggest that at the typical flow of 0.9 m^3/min (230 gpm) or less, the Mn concentration in the Wetland 1 effluent might be virtually zero. However, it does create an interesting operational dilemma.

Table 3. Estimated Wetland No. 1 effluent quality at various flow rates

Flow m^3/min (gpm)	Estimated Effluent Iron (mg/L)	Estimated Effluent Manganese (mg/L)
4.54 (1200)	0.86	3.0
4.16 (1100)	0.01	3.0
3.41 (900)	0.0	2.6
2.27 (600)	0.0	2.0
1.14 (300)	0.0	0.6
0.87 (230)	0.0	0.0 ??
0.11 (30)	0.0	0.0 ??

During most of the year, the Mn concentration entering Wetland 2 will be very depressed as most of the Mn would be removed in Wetland 1. Operationally, Wetland 2 will be starved for Mn under typical conditions. In order to replenish or sustain manganese oxide coatings on the limestone in Wetland 2, Wetland 1 needs to be periodically by-passed. The final design includes this operational control feature. It is unknown how often by-passing at low flow should occur, but a rotating schedule of partial by-passing Wetland 1 for about one week per month is a reasonable schedule.

Expected Aerobic Wetland 2 Effluent Water Quality

At the typical flow rate of 0.9 m^3/min (230 gpm), all the Fe is removed by the time the water reaches Wetland 2 and this applies to Mn as well. At peak flow, only about 0.6 mg/L of Mn would be removed in Wetland 2 based on conservative bench scale data. The hydraulic retention time in Wetland 2 at all flow rates is about five hours. The cumulative retention time in both wetlands is about nine hours which satisfies the As removal criterion with a significant safety factor.

Again, the mass balance model results suggest that at the flow of 1.14 m^3/min (300 gpm) or less, the Mn concentration in the final PTS effluent might be virtually zero. At higher intermittent flow rates, it is uncertain that the Mn removal will meet the effluent standard. Clearly, there should be a significant portion of the wetland zone that will be coated with manganese oxide based on the model results and that scavenging of secondary COCs under nearly all flow conditions is expected.

Table 4. Estimated Wetland No. 2 effluent quality at various flow rates

Flow (gpm)	Estimated Effluent Iron (mg/L)	Estimated Effluent Manganese (mg/L)
4.54 (1200)	0.0	2.4
4.16 (1100)	0.0	2.3
3.41 (900)	0.0	1.7
2.27 (600)	0.0	0.8
1.14 (300)	0.0	0.0 ???
0.87 (230)	0.0	0.0 ???
0.11 (30)	0.0	0.0 ???

System Commissioning

During commissioning it will be important to maintain standing water in Wetland 1 and 2 to preserve the viability of transplanted willows support the deposition of manganese oxide. It is also critical to return water to the Magenta Drain outfall so that is does not become dry. A temporary irrigation system is planned for use in this situation if needed. Clearly, commissioning the system would be best when flows are somewhat higher than the typical flow of 0.9 m^3/min (230 gpm).

Otherwise, no special startup procedures are anticipated.

Operation and Maintenance Considerations

One of the primary O&M activities will be the monitoring and removal of accumulated sludge in the settling pond. This was discussed in the Design Basis Report (Golder, 2010b) and is expected to be necessary once every four years.

Secondary O&M activities may include thinning of vegetation in Wetland 1 and periodic by-passing of Wetland 1 water to Wetland 2 as previously discussed. Details of these activities will be provided in the O&M manual for the system.

Closing Remarks

The goal of this project is to cost-effectively meet some very stringent discharge criteria using passive treatment methods. To the authors' knowledge, a PTS of similar scope and effluent goals has never been constructed. However, the individual processes of iron hydroxide settling, As adsorption, manganese oxide adsorption to limestone, and secondary contaminant adsorption to manganese oxide are well documented in the literature. These collective mechanisms were all likely responsible for the success of the wetland bench study in meeting the required effluent standards. It is likely that they will function equally well, if not better, at the design flows anticipated at the Magenta Drain PTS.

The spinoff benefits of passive treatment at the Empire Mine State Historic Park include:

- implementation of a "green technology" that minimizes long term carbon footprint
- the treatment facility blends into the existing parkland habitat with minimum hiking trail disruption and park user noise and visual impacts
- it minimizes local infrastructure impacts for roads, traffic, power, water, and sewer
- the process uses no chemicals and once the water reaches the settling pond, all flows are by gravity

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