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WETLANDS FOR INDUSTRIAL WASTEWATER TREATMENT AT THE SAVANNAH RIVER SITE

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ABSTRACT

The A-01 effluent outfall, which collects both normal daily process flow and stormwater runoff from a industrial park area, did not meet the South Carolina Department of Health and Environmental Control (SCDHEC) National Pollutant Discharge Elimination System (NPDES) permit limits for metals, toxicity, and total residual chlorine at the outfall sampling point. Copper was the constituent of primary concern and the effluent consistently failed to meet that NPDES limit. Installation of a constructed wetland system including a basin to manage stormwater surges was required to reduce the problematic constituent concentrations to below the NPDES permit limits before the effluent reaches the sampling point.

Both bench-scale and on-site pilot scale physical models were constructed to refine and optimize the preliminary design as well as demonstrate the effectiveness of this approach prior to construction, which was completed in October 2000.

The constructed treatment wetlands system has proven its ability to treat industrial wastewaters containing metals with low O&M costs since there are no mechanical parts. With an anticipated life of over 50 years, this system is exceptionally cost effective.

BACKGROUND

The Atomic Energy Commission (now the Department of Energy) created the Savannah River Site (SRS) located in South Carolina in the early 1950's to produce nuclear material. For more than two decades, the SRS mission has included the environmental restoration of the site. In the past decade, the mission of the facility has evolved to research and applied environmental technology transfer. Coupled with this mission has been compliance with state and federal regulations including the permitting of discharge outfalls.

The A-01 effluent outfall discharge consists of daily process flows (0.972 MGD) from eight identifiable waste streams plus stormwater flows from the Savannah River Technology Center (SRTC) Technical Area and the eastern part of the 3/700 Area. At the beginning of this project, the outfall did not meet the SCDHEC NPDES permit limits for metals, toxicity, and total residual chlorine at the outfall sampling point. Copper was the constituent of primary concern because it consistently failed to meet the NPDES limits and was a likely contributor to the toxicity exceedences. An evaluation of the A-01 discharge determined that storm water runoff from the STRC parking lots was contributing copper to the waste stream so a system was required that would manage stormwater surges as well as decrease the problematic constituents concentrations below the NPDES permit limits before the effluent reached the sampling point. The location of the future A-01 outfall (or point of compliance) was located in the effluent channel just upstream from the confluence of the effluent channel with an unnamed tributary of Tim's Branch, approximately $^{2}/_{3}$ mile downstream from the historic A-01 outfall location.

CONSIDERATION OF ALTERNATIVES

Before the project began, a thorough analysis of alternatives for mitigation of the A-01 effluent outfall (wastewater) was conducted in 1998. Alternatives that were considered for mitigation of the targeted constituents in the wastewater included:

- Receiving system investigations,
- Corrosion inhibitors and pH adjustment,
- Rerouting waste stream,
- Ion exchange,
- Blending waste streams,
- Movement of the compliance point, and
- A constructed wetlands system.

After these alternatives were evaluated, both independently and in combination, the preferred strategy was selected based on consideration of technical feasibility, economic factors, regulatory issues, and implementation time. With the exception of one alternative, each had significant technical difficulties or was cost prohibitive (both economically and environmentally). Only the constructed wetlands system was considered to be a viable alternative and was recommended for implementation.

DESIGN OBJECTIVES AND TREATMENT MECHANISMS

The design objective of this system was to treat targeted constituents of the A-01 effluent outfall (including stormwater) to comply with NPDES permit limits of the specific targeted constituents presented in Table 1.

Table 1 - Target Constituents and Associated NPDES Compliance Limits

Constituent	NPDES Limit	Average Mass Discharged
Copper	22 µg/L avg.	0.14 Kg/Day
Lead	5 µg/L avg.	<0.01 Kg/Day
Mercury	0.013 µg/L avg.	<0.0003 Kg/Day
Zinc[1]	250 µg/L avg,	0.21 Kg/Day
Total Residual Chlorine	12 µg/L avg.	<0.2 Kg/Day
Total Suspended Solids	20 mg/L	8 Kg/Day
Biochemical Oxygen Demand	10 mg/L avg.	<7 Kg/Day
PH	5.0-8.5	-------
Oil and Grease	10 mg/L avg.	-------
Trichloroethylene	0.27 mg/L avg.	<7 Kg/Day
Tetrachloroethylene	0.27 mg/L avg.	<7 Kg/Day
Chronic toxicity at in-stream waste concentration of 93.4%	0 (no toxicity)	-------

[1] Anticipated limits

Flow Management (Control)

Water management, both high and low flows, is crucial to the success of every constructed wetland project and this one was no different. The high flows were derived from runoff calculations of a 25-year, 24-hour precipitation event and the low flows were based on the dry weather minimum process flow. The maintenance of the structural integrity of the constructed wetlands due to hydraulic forces and minimum hydraulic residence time required for treatment were the primary concerns associated with managing the uncontrolled stormwater surges. The design addressed these concerns by proposing a flow management basin. The flow management basin was designed contain the design precipitation event and to release the commingled storm water and process water gradually over time. Further, the flow management basin will manage the daily changes in process to assure that all water has sufficient contact time in the construct treatment wetlands.

The primary concern during the summer dry periods with minimal rainfall is maintenance of water depth in the constructed treatment wetlands. Every acre of constructed treatment wetland has minimum daily water needs, thus it was important that the daily minimum process flow be compared with the constructed treatment wetlands consumptive use (i.e., evapotranspiration) to ensure that the constructed treatment wetland is not over built.

Treatment of Targeted Constituents (Transfers and Transformations)

Based upon NPDES permit targeted constituents, the materials or parameters designated for primary design consideration included copper, total residual chlorine, total suspended solids, and chronic toxicity. The design process simultaneously evaluated all of the constituents and required treatment mechanisms to ensure that mutually exclusive or antagonistic treatment approaches are not employed. The wetland treatment mechanisms are described in a number of references including USEPA (2000).

Copper

The environmental fate and effects of copper in aquatic systems have been studied extensively since it is both an essential micronutrient and a potentially toxic substance (Lewis 1992). Copper is ubiquitous in rocks and minerals in the earth's crust, hence it has a lithic biogeochemical cycle. Weathering of copper minerals results in natural surface water background concentrations usually well below 20 µg Cu/L (USEPA 1980) and sediment concentrations ranging from 1 to 10 mg Cu/kg. However, much of the copper entering aquatic systems is due to anthropogenic activities (Moore 1990; Dugan 1991), thus, copper bioavailability in sediment has been a focus of recent research (Deaver 1995; Deaver and Rodgers 1996; Suedel et al. 1996; Huggett et al. 1999).

When copper enters aquatic or wetland systems in solution, it speciates into numerous forms or compounds as it interacts with components of the ecosystem. Several processes determine the fate of copper in wetlands: complex formation, sorption to hydrous metal oxides, clays, or organic materials, formation of insoluble species (e.g., metal sulfides), and bioconcentration / bioaccumulation. Because of its lithic biogeochemical cycle, copper has a high affinity for sediments and a short residence time in solution. In this system, the copper is sequestered from the aqueous matrix to the hydrosoil and allowed to speciate to nonbioavailable forms.

Total Residual Chlorine

Chlorine exists predominantly as hypochlorous acid and hypochlorite ion, referred to as "free chlorine residuals" at the pH of most natural waters. These free residuals react readily with ammonia and other nitrogenous compounds to form "combined chlorine." Collectively, free and combined chlorine are considered "total residual chlorine" (TRC) (Sawyer and McCarty 1967; APHA et al. 1996). Chlorinated wastewater effluents normally contain only combined chlorine due to the reactivity/volatility of free chlorine residuals (APHA et al. 1996). Since TRC is present below the A-01 effluent outfall, it is likely that this exists in the form of chloramines (combined chlorine). To mitigate these compounds, this constructed wetlands system provides numerous binding sites (hydrosoil and plants) for chlorine residuals followed by microbial degradation.

Total Suspended Solids

The process used for treatment of total suspended solids (TSS) in the constructed wetlands system is based on Stokes' Law. As the velocity of the water flow into the flow management basin and constructed wetlands decreases, particulates can settle from the water column. Thus, settleable and suspended solids are removed from the A-01 effluent by physical sedimentation and filtration processes. The upstream flow management basin will settle a significant portion of suspended solids from the water column before entering the constructed wetlands. If water leaving the retention basins still contains appreciable amounts of suspended matter, the constructed wetlands will provide filtration (by wetland vegetation) to further remove residual suspended solids.

Chronic Toxicity

The chronic toxicity targeted for treatment in the A-01 Outfall was identified as largely due to bioavailable copper. Since the observed toxicity was manifested as decreased reproduction by *Ceriodaphnia dubia* in 7-day exposures, it is unlikely that any other constituents contributed significantly to this situation. As discussed above, the design effectively sequestered divalent metals such as copper in sulfidic and nonbioavailable forms. The efficacy of this approach (constructed wetlands) for mitigation of toxicity due to divalent metals has been demonstrated in both the laboratory and the field (Sinicrope et al. 1992; Deaver 1995; Hawkins et al. 1997; Gillespie et al. 2000).

DESIGN OF THE SYSTEM

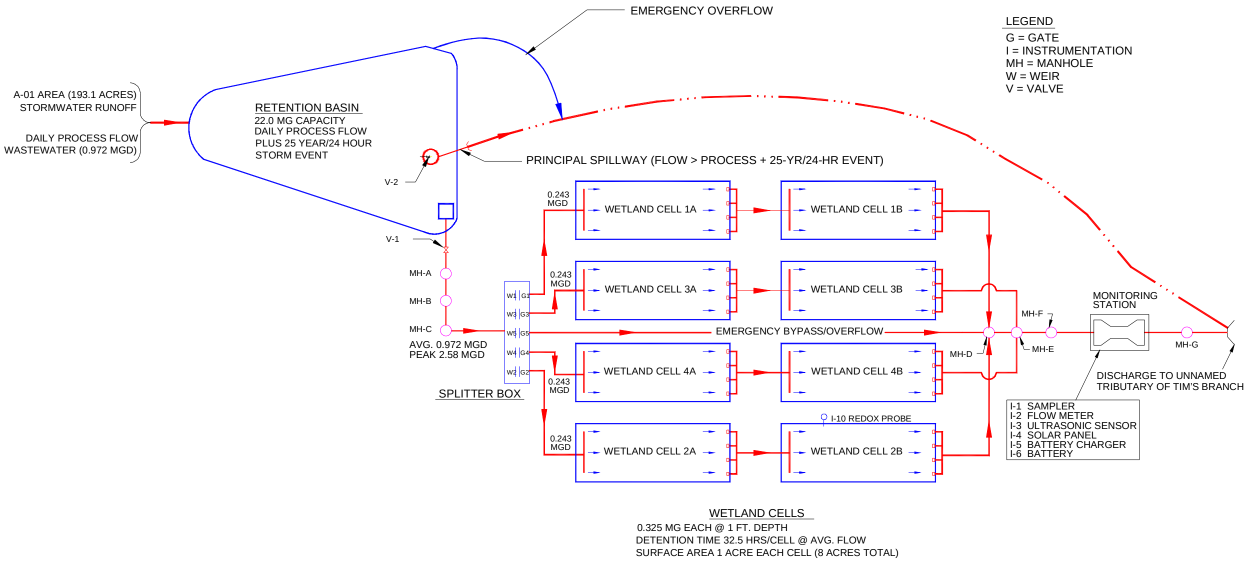
The design of the treatment system consisted of a retention basin to manage the stormwater runoff flows and a series of four separate treatment trains each consisting of two 90 foot by 484 foot wetland cells. Figure 1 shows a process flow diagram of the system. The entire system is gravity fed and the only moving parts are two gate valves and a solar-powered sampling/flow monitoring station.

Flow Management Structures

The normal process flows comprising the A-01 effluent outfall are as follows:

Normal Process Flows	572,000 GPD	
Air Stripper Flow	400,000 GPD	(Assume 24- hr, 365- days/yr. Operation)
Total Process Flow	972,000 GPD	

Figure 1 - Process Flow Diagram for Constructed Treatment Wetlands System



The flow management basin was designed to retain runoff from a 25-year recurrence interval storm event over a 24-hr period and release the water as necessary to support/protect the wetlands system to maintain a relatively constant depth of 30 cm. Stormwater flows from the watershed were calculated as follows:

- Stormwater Volume: 21 million gallons in 24-hr period
- Based on 6.1” of rain over 24-hr period (EarthInfo, 1995; Eliasson, 1997)

As discussed previously, both the maximum (high) flow and minimum (low) flow situations were important for design of this constructed wetlands system.

High Flow Management

The design high flow for the treatment system is approximately 22 million gallons, which was determined by adding the process flows to the stormwater flow; therefore, a single flow management basin was designed to regulate the 22 million gallons of stormwater and process flow combined. This high flow was best regulated in the watershed as far upstream as practical.

Low Flow Management

An important part of this constructed wetlands design is maintenance of water depth in the wetlands during periods of little or no rainfall. The flow management basin was utilized and managed to maintain flow during low flow periods by damping diurnal variations as well as to dampen hydraulic surges during high flow. The design low flow for this constructed wetlands system was 222 gallons per minute, or 0.320 MGD.

An evaluation of the soils to provide a relatively impermeable barrier for the bottom of each cell revealed hydraulic conductivities in the 10^{-5} to 10^{-6} cm/sec range. While low, there was the potential for effluent loss via infiltration and evapotranspiration of the flow management basin and the wetland cells to exceed the design low flow. Accordingly, the design of the cells reflected the hydrosoil layer being underlain by a compacted soil liner containing ≥ 30% clay to decrease permeability. After finding insufficient material available at SRS, it was decided that a geosynthetic clay liner (GCL) was the most cost-effective means to control infiltration in both the wetlands cells and in the normal flow pool area of the flow management basin. The sealing of the cells and flow management basin to prevent infiltration provided sufficient cause for the SCDHEC to waive the groundwater monitoring well requirement saving both construction expense as well as the cost of long-term monitoring.

Integration of Targeted Constituents and Proposed Treatment Strategies

Integrated review of the independent targeted constituents treatment strategies of this effluent indicated no incompatibilities in this design. The metals, primarily copper, are sequestered in a similar manner in that they are transferred to organic ligands and settled to sediments or they will be transformed into very stable metal sulfides. It will be important to sustain desired redox conditions in the wetland hydrosoils to accomplish formation of metal sulfides and prohibit formation of methyl mercury. Since most (if not all) of the observed toxicity was due to the presence of metals (primarily copper), no toxicity from this source has been observed after treatment. Initially, TSS was being removed primarily by settling in the flow management basin; however, filtering within the constructed wetlands system increased as the plant density increased with system maturity during 2001. Similarly, BOD was being initially removed primarily by settling and *in situ* degradation; however, filtering within the constructed wetlands system increased in 2001 as the plant density increased. Total residual chlorine (largely combined chlorine) was degrading similarly. The constructed wetlands system has not significantly altered the pH of the effluent, and the circumneutral pH is compatible with all other treatment strategies.

The kinetics of the transfers and transformations of the targeted parameters are an important consideration in design of this constructed wetlands system. The fundamental design consideration is the understanding that “in order to treat a material in a constructed wetlands system, that material must be retained within the system for sufficient time (e.g., for a sufficient number of half-lives) for the targeted material to be decreased to the desired level” (Rodgers and Dunn 1992). The treatment kinetics relate directly to a volume of effluent that can be treated in a given duration or amount of time, and this volume can be directly translated to a specific area that the constructed wetlands must occupy to achieve the desired treatment. A hydraulic retention or residence time (HRT) for the A-01 effluent stream needed for the constructed wetlands treatment system to achieve the project objectives is between 24 hours and 48 hours.

Selection of Wetland Macrofeatures

Successful performance of treatment wetlands is based on appropriate integration of wetland macrofeatures: (1) hydrosoil, (2) hydroperiod, and (3) vegetation (Hawkins et al., 1997; Gillespie et al., 2000). The fundamental principle of the integrated design of treatment wetlands is combining these macrofeatures such that transfers and transformations of targeted aqueous constituents are thermodynamically possible or likely. Critical to this constructed wetlands system will be sustaining the desired hydrosoil redox potential to prevent methylation of mercury, while maintaining sufficiently reduced conditions to promote formation of insoluble, biounavailable species of other metal constituents. The following macrofeatures were integrated into this constructed wetlands system.

Hydrosoil

Hydrosoil selection is based on: (1) pH and redox considerations, (2) ability to sequester metals and promote other mitigation processes (e.g., aerobic microbial degradation of BOD), (3) appropriate chemical and physical characteristics (e.g., organic matter content), (4) minimal background contamination, (5) compatibility with selected wetland plant species, (6) availability of nutrients for plant growth, and (7) location and availability (including transportation costs).

Soil types along the A-01 effluent stream to the confluence with Tims Branch consist primarily of Fuquay sand (2 to 6 percent slopes), Lucy sand (2 to 6 percent slopes), and Vaucluse-Ailey Complex (6 to 10 percent slopes), with a small area of Dothan sand (2 to 6 percent slopes) and a narrow flood plain with many inclusions. These soils are made up of Vaucluse, Troup, and Ochlockonee series (Rogers 1990). These soils were suitable as wetland hydrosoils for plant culture after amendment with organic matter (mulch) to promote sufficiently reduced conditions for sequestration of metals. Lime was also added to locally recommended levels for crops to maintain circumneutral pH. The porosity of these soils offered by their sandy-loam character allowed sufficient reduction of the hydrosoil to maintain the desired redox potential. Detailed soil analyses revealed that these soils were typically nutrient-poor, thus it was necessary to add nutrients in the form of controlled release fertilizer (e.g., Osmocote®). The hydrosoil thickness for plant growth and treatment in the constructed wetlands was selected to be approximately 48 cm deep.

Hydroperiod

Based on process flow rates and availability of land for treatment wetlands construction, a hydroperiod was needed that would facilitate the desired transfers and transformations of targeted A-01 effluent constituents, as well as meet the hydraulic requirements of the selected wetland vegetation. Water depth maintained in the wetlands is important due to its influence on hydrosoil reduction or oxidation. A relatively constant water depth of 30 cm was needed for this constructed wetlands system to maintain reduced conditions necessary for metal attenuation from the aqueous matrix. Maximum hydraulic retention time (HRT) desirable was set at 48 hours to allow any kinetically limited transfers or transformations to proceed to the fullest extent possible.

Based on the ideal 48 hour HRT needed to achieve the desired level of treatment and the normal daily process flow rate, it was determined that three treatment trains each containing two 1-acre cells were needed. The design utilized eight 1-acre cells to provide redundancy and maintain full treatment capacity with two cells off line. It is important to note that as berm height is increased in the constructed wetlands, the water storage capacity of the system is also increased. If needed, an additional 2 feet of water can be temporarily stored (up to 3 weeks) in the constructed wetlands (giving additional storage of 16 acre-feet of water or ~ 5 million gallons).

Vegetation

Plant species selection was based on previous knowledge of plant characteristics, experience, and scientific literature. Selection criteria for the recommended wetland vegetation included: (1) potential effects on hydrosoil pH and redox; (2) compatibility with selected hydrosoil; (3) compatibility with local climate; (4) ability to tolerate hydroperiod fluctuations (i.e., water depth and HRT); (5) compatibility with objective (i.e., provide detritus to yield the reducing power to maintain reduced conditions without contributing significantly to BOD); (6) resistance to herbivory; (7) cost and availability; and (8) non-exotic species.

In addition, the wetland vegetation needed to contribute organic carbon in the form of detritus to provide reducing energy to maintain the negative redox in the hydrosoil and each year provide new binding sites for metals and organics. Consequently, the detritus needed a half-life of approximately 6 months to 1 year. Consequently, an accreting wetlands system was established in which the hydrosoil organic carbon (i.e., peat) increases at an incremental rate through time.

Indigenous vegetation was surveyed and evaluated for ability to meet these criteria and a bulrush (*Scirpus* sp.) was selected. The role of *Scirpus* in remediation of Cu, Pb, and Zn has been established in previous studies (Hawkins et al. 1997; Gillespie et al. 2000) with objectives consistent with those for the A-01 effluent outfall. In addition to providing necessary redox conditions for sequestering metals in the hydrosoil, vegetation density at full maturity will influence the wetlands' ability to promote sedimentation of suspended solids and associated BOD. Figure 2 shows the dense root zone of a mature giant bulrush (*Scirpus Californicus*) plant.

Figure 2 – Root Zone of Mature Bulrush Plant

Wetland Treatment Cells

The constructed wetlands were arranged in pairs so water flows serially from one wetland cell to the next (Figure 1). Each of the eight constructed wetland cells has a "footprint" of 1 acre with a minimum length to width relationship (aspect ratio) of 4 to 1 in order to maintain plug flow and minimize ineffective treatment areas ("dead" zones) which would short-circuit treatment. This alternative and arrangement was preferred because:

- The independent wetland cells can be taken "off-line" for maintenance if necessary.
- This arrangement provided maximum HRT and associated treatment time to maximize treatment efficiency.
- These eight wetland cells were cost efficient to construct because plumbing and flow control structures were minimized.

Construction Material Selection

It was important to ensure that the contractor used inert building materials (e.g., concrete, PVC, FRP, HDPE) to avoid leaching of metals and other contaminants into the A-01 effluent stream. Materials that were essential to avoid included those with galvanized or metal coatings, painted surfaces, bituminous coatings, and treated wood. The design also included as many prefabricated components as possible to control costs and reduce construction time.

A number of factors were considered in developing the planting specification including: the availability, cost, source distance from the site; maturation rate of the plant; tolerance of the plant to transport and replanting; and time available for system maturation. Given the criterion of needing a fully functioning system by fall 2001, the planting specification required the use of live plants obtained from a nursery.

SCALE MODELING OF THE SYSTEM

In an effort to refine and optimize the preliminary design, both bench-scale and on-site pilot-scale physical models were constructed. The results of both of the models demonstrated the effectiveness of this system and confirmed the design prior to construction. A photograph of the bench-scale model is shown in Figure 3. The bench-scale study with waters collected from the A-01 effluent outfall illustrated significant decreases in observed toxicity after treatment of the effluent in a constructed wetland system. Figure 4 shows the on-site pilot-scale model that was constructed. These systems provided key insights into the system that helped refine the design before construction began.

CONSTRUCTION OF THE SYSTEM

Construction of any natural system requires careful project planning and construction scheduling. As with any plant, hydrophytes are subject to transplant shock and climate stress. Therefore it is important to schedule planting during times when these impacts can be minimized to improve survival rates. Natural systems need a minimum of one complete growing season to mature to a point that the desired processes will be fully functional. In the case of the wetland construction

Figure 3 – Bench-Scale Physical Model

Figure 4 – Pilot-Scale Physical Model

at SRS, the climate dictated that planting of the cells be completed no later than the end of June to minimize planting stress on the transplanted hydrophytes. The primary factors that influence constructed wetlands maturation time include initial planting density, water control structures, availability of water, and length of remaining growing season. Figure 5 shows a close-up of one of the cells during planting.

The first task undertaken by the contractor was the construction of the wetland cells in order to meet the late spring/early summer planting window for the giant bulrush necessary to achieve the summer 2001 deadline of a fully functioning system. Figure 6 shows an aerial photograph of the system as it neared completion in September 2000. The completed wetland cells can be seen in the foreground and the construction of the embankment for the flow management basin is visible in the background.

Figure 5 – Wetland Cell During Planting

Figure 6 – Aerial Photograph of Wetland System

OPERATION, MAINTENANCE, AND MONITORING CONSIDERATIONS

The flow management basin and constructed wetlands are designed to function in concert. In order to ensure adequate performance to achieve the treatment objective, it is important that the system is operated and maintained so the desired processes will occur.

Flow Management Basin

This structure (flow management basin) was designed to assist performance of the treatment system during high and low flows as well as average daily flows by reducing peak storm flows and damping out diurnal flow variations. As mentioned previously, controlling the flow into the constructed wetlands is crucial for treatment performance. The storage capacity of the flow management basin can be regulated to assist with high flows as well as low flows.

During seasons or periods when high rainfall is expected, the flow management basin should be maintained near empty for maximum storage capacity (approx. 22 million gallons). The downstream constructed wetlands with all treatment trains on-line were designed to process about 1.3 million gallons per day. The constructed wetlands have an additional capacity of ~5 million gallons and provides considerable flexibility for dealing with high flow events. During seasons or periods when little rainfall is expected, the influent to the constructed wetlands can be maintained at the minimum base flow from the process stream (~0.3 million gallons per day).

Additional maintenance requirements for the flow management basin included: (1) observation and removal of accumulated debris from both the low-flow outlet structure and the primary spillway structure; (2) observation and maintenance of dam to prevent erosion; (3) observation and removal of burrowing animals; and (4) removal of any trees or scrubs that may begin to grow on the embankment.

Constructed Wetlands

The constructed wetlands require relatively little maintenance except for a few items that include: (1) observation and clearing of the inflow and outflow structures, (2) observation and maintenance of berms to prevent erosion, (3) observation and removal of burrowing animals, and (4) observation and control of excessive herbivory (insects, mammals, etc.). Relatively simple approaches can deal with periodic events such as excessive herbivory. For example, application of a mild insecticide such as Sevin® dust with a relatively short half-life may be necessary in cases of extreme herbivory due to insects.

Operation of the constructed wetlands consists primarily of adjusting water depth for maintenance of the desired redox potential, however given that the a wetland system is usually very stable, the need for adjustment should be infrequent. Redox potential of the constructed wetlands hydrosoil can be monitored with simple platinum electrodes (Faulkner et al. 1989) that can be "permanently" installed to minimize stabilization time. If the redox potential is too low, water depth will be decreased in 4-inch increments and conversely if the redox potential is too high, then the water depth can be increased in 4-inch increments.

Monitoring of the constructed wetlands consists primarily of performance monitoring and redox measurements with depth adjustments. During the initial maturation period, a simple 1-meter grid, as shown in Figure 7, was used to record plant growth by counting the number of shoots. Other initial monitoring that is being conducted includes collection, as shown in Figure 8, and analysis of the hydrosoil. The flow through the constructed wetlands is measured using a parshall flume located between the wetland cells and the outfall.

Figure 7 – One-Meter Grid for Measuring Plant Growth

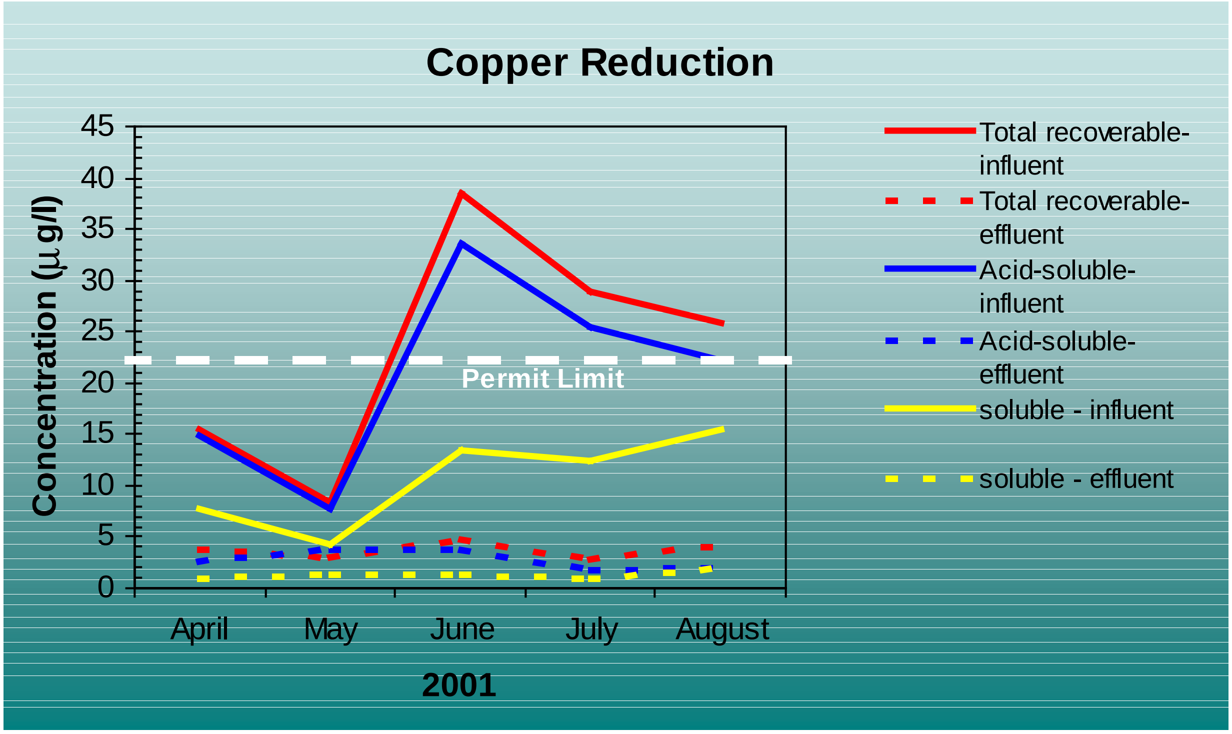
Figure 8 – Sediment Sampling for Monitoring

Long-term monitoring relative to performance and general observations is relatively simple and straightforward. Measuring the target constituents in the influent to the constructed wetlands and comparing those results with measurements from the constructed wetlands effluent will determine performance of the constructed wetlands in terms of treatment of the targeted constituents and achieving the objective. Long-term monitoring of the redox will provide an early warning if the biogeochemistry begins to change and adjustments are needed to maintain performance.

SYSTEM PERFORMANCE IN 2001

During 2001, regular monitoring of the system began with samples being collected monthly by Clemson University. Figure 9 shows the performance of the system to remove copper, the effluent constituent of greatest concern. Toxicity results from the same time sampling events showed an influent that was resulted in 100% mortality for *Ceriodaphnia dubia* in 7-day exposures and a system effluent that showed 0% mortality.

Figure 9 – 2001 Performance Results



CONCLUSIONS AND BENEFITS

The constructed treatment wetlands system has proven its adaptability to treat industrial wastewaters containing metals. The scale-model studies provided key insights into the HRT and other design features needed to treat the A-01 effluent outfall waste stream, thus allowing the most efficient design to be constructed. Constructed wetlands have the advantage of very low O&M costs since there are no mechanical parts and the capital cost of this system was less than the other options evaluated. With an anticipated life of over 50 years, this type of system is exceptionally cost effective.

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