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EXECUTIVE SUMMARY

INTRODUCTION

The major findings and recommendations of the Sacramento Constructed Wetlands Demonstration project (SC WDP), conducted by the Sacramento Regional County Sanitation District (SRCSD), are presented in this document.

An overview of the demonstration wetland project along with background information on treatment wetlands and trace metals is presented in the initial section of the executive summary. A discussion of the project results follows. Lastly, the major findings of the project are summarized.

Project Objectives

The SCWDP is a five-year project of the SRCSD that was conducted from January 1994 to December 1998. Project emphasis was on characterization of the performance of treatment wetlands for trace metals removal. Objectives of the project are:

I. Characterize the performance of treatment wetlands for water quality improvement

II. Identify the fate of trace metals within treatment wetlands

III. Develop and evaluate treatment wetlands management methods

Sacramento Regional County Sanitation District

SRCSD manages wastewater conveyance, treatment, discharge and water reuse for the greater Sacramento region. The SRCSD owns and operates the Sacramento Regional Wastewater Treatment Plant (SRWTP) located in Elk Grove, California. With an average daily flow of approximately 150 Mgal/d, the SRWTP is the largest discharger to inland surface waters in California.

Demonstration Wetlands Project Development

SRCSD's interest in treatment wetlands developed primarily in response to the federal promulgation of ambient water quality criteria for surface waters spurred by the 1987 Amendments to the Clean Water Act. The stringent metals limits included in the federal criteria posed a threat of discharge violation and would require additional treatment facilities, such as chemical precipitation, filtration or membrane technologies.

Although the numeric criteria developed by the State of California in the form of the 1991 Inland Surface Waters Plan (IS WP). would eventually be rescinded, the SRCSD recognized the need to identify cost-effective approaches to achieve compliance with stringent discharge criteria for trace metals and other pollutants. At the same time, SRCSD implemented a Priority Pollutant Pretreatment Program to address metals loadings concerns. The pretreatment program has been highly successful in reducing metals loadings over the previous five years despite a concurrent increase in flows.

Although treatment wetlands are widely recognized to effectively remove organic matter and suspended solids, little information was available regarding the performance of these systems with regard to trace metals removal. Furthermore, very little was known about the long-term accumulation of trace metals in these engineered natural systems. Additional information was needed to create a rational basis for the development of design criteria, capital costs, and operation and maintenance costs. The SRCSD, with the support of wetland mitigation funds offered from EPA, undertook a demonstration treatment wetlands project to characterize the performance of these systems with regard to metals removal.

Since the development of the project, the EPA has proposed revised ambient water quality criteria for California in the form of the California Toxics Rule (CTR). California is in the process of incorporating these criteria into a revised version of the ISWP that has yet to be adopted.

Sacramento Constructed Wetlands Demonstration Project Facilities

A three-phase project was conceived consisting of: 1) planning and model development, 2) design, construction and startup, and 3) operation. An area in the northeast corner of the bufferlands that surround the SRWTP was chosen to site the 22-acre SCWDP Facilities.

Multiple wetland cells were incorporated into the design to allow experimental flexibility. The primary function of the multiple wetland cells was to allow long-term comparison both among and within the following five distinct hydraulic operating regimes; 1) fill and draw, 2) recycle, 3) overland flow, 4) plug flow and 5) subsurface flow. A project control cell that received groundwater was provided and a two-acre habitat cell received effluent from the treatment cells prior to return to the SRWTP for discharge. The eleven 1,260 ft long by 50 ft wide wetland cells were planted by applying soil containing seeds and rootstock from a nearby wildlife refuge. Lush and fast growth of tale (*Scirpus sp.*) and cattail (*Typha sp.*) ensued.

Ultraviolet-light disinfected secondary effluent was first applied to the treatment wetland cells in March 1994. The pump station to the SCWDP and the facility itself were designed to handle 1.2 Mgal/d. A comprehensive monitoring program was implemented to monitor hydraulic components, water quality, sediment quality, vegetation, habitat diversity and vectors. Ongoing programs of vector control and vegetation management were also implemented on an annual basis. Summary project reports were published annually.

Public Outreach

The SCWDP served as both an educational tool and a public relations mechanism. The facility was used to introduce children from neighboring schools to the features of the treatment wetlands and the values of natural systems. The project also facilitated a Ph.D. dissertation and two masters thesis on wetland processes for one U.C. San Francisco and two U.C. Davis graduate students.

Interest in treatment wetlands as low cost natural systems for treatment of wastewater also Attracted engineers to tour the facilities from throughout the United States as well as from China, Mexico, Italy, Australia, and Japan. The project received the top award in the 2000 Engineering Excellence competition from the Civil Engineers and Land Surveyors of California (CELSOC), a 1997 Research Achievement of the Year by the California Water Environment Association, and an Outstanding Achievement Award at the Central California Regional Science and Engineering Fair.

Continued Use

The fifth and final year of monitoring at the SCWDP was completed in December 1998. The SRCSD has placed the project on standby while simultaneously investigating opportunities to continue the use of the wetlands facility. A detailed investigation of capital costs and operation and maintenance costs was developed as part of the continued use effort. To date, four potential uses have emerged from this investigation:

I. Provide secondary effluent polishing prior to discharge to onsite creeks.

II. Continue research and monitoring to further the initial Demonstration Project objectives.

Ill. Provide a facility for participating organizations to support scientific research.

IV. Provide treatment of nitrate-laden leachate from the District's Dedicated Land Disposal (DLD) site.

Summary of Treatment Wetland Technology

The performance of constructed wetlands for the improvement of water quality and the removal of conventional pollutants from municipal wastewater has been documented in numerous case studies, design manuals, and texts. For further guidance, the reader is directed to the following texts:

- Treatment Wetlands, Kadlec, R.H., and R.L. Knight (1996), CRC Press
- Wetlands, Mitsch, W.J., and Gosselink (1993), Van Nostrand Reinhold
- Natural Systems for Waste Management and Treatment, Reed, S.C., Crites, R.W., Middlebrooks, E.J. (1995), McGraw Hill

Review of the five years of project data indicate that the SCWDP operated within performance ranges reported in the literature for organic matter, total suspended solids. ammonia-nitrogen and phosphorous removal.

Trace Metals Criteria and Characterization

Because the project was operated as a zero-discharge demonstration facility, it was not necessary to comply with any particular discharge ciiteria. In the interest of evaluating project performance, the following criteria or guidelines were applied.

Water Quality Criteria. Development of ambient water quality criteria for priority pollutants for surface waters is a requirement of the Clean Water Act. The State of California's 1991 ISWP was eventually rescinded in response to legal challenges, leaving California without ambient water quality criteria until the EPA issued the CTR in 1997. The state is in the process of updating and incorporating these criteria into a revised version of the ISWP that has yet to be completed.

Sediment Criteria. Sediment trace metals concentrations within the wetlands were compared to Probable Effects Levels (PELs) contained in the freshwater sediment quality guidelines compiled by the National Oceanic and Atmospheric Administration (NOAA). Wetland sediment trace metals concentrations were also compared to the values found in California's (Title 22) hazardous waste criteria as well as EPA's Part 503 biosolids limits.

PERFORMANCE OF CONSTRUCTED WETLAINDS

The SCWDP was monitored intensively for water quality, sediment quality, vegetation characteristics, and habitat use. The results of each of these monitoring components are sununarized in the following paragraphs.

Water Quality

The treatment wetlands were effective at removing a number of wastewater constituents from the water column.

Trace Metals. Influent and effluent from the treatment wetlands were routinely monitored for the presence of 15 trace metals: antimony, arsenic, copper, beryllium, cadmium, chromium, iron, manganese, lead, mercury, nickel, selenium, silver, thallium, and zinc.

The concentration of these trace metals entering the treatment wetlands were typically very low. Although a few metals in the SRWTP's secondary effluent exceeded the ISWP criteria at the outset of the project, none of the metals entering the treatment wetlands exceed the current CTR ambient water quality criteria.

With the exception of silver and lead, all metals entered the treatment wetlands predominantly in the dissolved form. Nickel and arsenic were present in the influent in a dissolved fraction of approximately 80 percent.

Comparison of effluent total metals concentrations with the criteria found in the CTR indicates complete compliance, with only copper approaching one-third of the average aquatic life criteria.

Of the nine trace metals measured, six metals (silver, cadmium, copper, mercury, lead and zinc) consistently exceeded mass removal rates of 60 percent. Concentration and mass removal rates for three trace metals (arsenic, chromium and nickel) steadily declined over the monitoring period.

The cause of the decreased removal performance for arsenic, chromium, and nickel is likely related to their presence in the wetland in a predominantly soluble form, and a chemistry that inhibits their removal from solution. Arsenic and nickel had the highest inlet dissolved metals fraction of all the metals analyzed.

Water column speciation investigations were conducted in 1997 on three trace metals: nickel, copper and chromium. Nickel was observed to enter the wetland in a predominantly dissolved and strongly organic-complexed form that is resistant to removal. Conversely, approximately fifty percent of the influent copper was in a dissolved and weakly organic-complexed form that underwent significant reduction in concentration upon passage through the treatment wetland. Although total chromium concentration was observed to undergo little removal upon passage through the wetland cells, hexavalent chromium was observed to undergo a 60 percent reduction.

Temperature. Effluent temperature control is important, as SRCSD must satisfy temperature criteria in their discharge to the Sacramento River. Water temperature also has a strong effect on biologically-mediated treatment performance and effluent ammonia toxicity. The high surface area to volume ratio and the long hydraulic detention times within the treatment wetlands contributed to a significant influence of ambient air temperatures on wetland water temperatures. A decrease in average wetland water temperatures was observed in eleven months of the year, with an annual average water temperature reduction of 3 ^{0}C. The cooling trend was strongest in the winter months when there was a significant difference between inlet water temperatures and ambient air temperatures.

This cooling effect is considered beneficial as it could lead to diminished thermal shock to aquatic organisms in the receiving water and increase the fraction of total ammonia that is in the ionized form, resulting in a decrease in overall toxicity.

Organic Matter. Overall, the treatment wetlands demonstrated a 55 percent likelihood of compliance with a 10/10 BOD_5/TSS limit and a 93 percent likelihood of compliance with a

30/30 BOD_5/TSS limit. Organic matter, measured as biochemical oxygen demand (BOD_5), undergoes a four-fold reduction through the treatment wetlands. An average influent BOD_5 concentration of
24 mg/L was reduced to an average effluent BOD_5 concentration of 6.5 mg/L. Wetlands effluent BOD_5 concentrations varied considerably over time in response to variations in influent loadings and environmental factors that influence the production and release of carbon within the wetlands.

Influent total suspended solids were generally below 10 mg/L. With such low influent levels, the total suspended solids generally increased upon passage through the treatment wetlands as a result of algae growth, sediment suspension and production of detrital material. Effluent total suspended solids concentrations varied in response to stochastic inputs and changing environmental conditions. A clear trend towards increased effluent total suspended solids concentrations was observed in the summer, and is likely attributable to increased algae production and vegetation decomposition during this period.

Dissolved Oxygen and pH. Dissolved oxygen levels within the treatment wetlands generally were below 2 mg/L. However, the diurnal influences of algae photosynthesis and respiration were apparent, particularly within the open water areas. The pH within the treatment wetlands was generally around 7.0, with diurnal fluctuations observed within the open water areas.

Nutrients. Wastewater treatment at the SRWTP does not include nitrification; consequently, wetland influent ammonia-nitrogen levels averaged 14 mg/L and nitrate-nitrogen was practically nonexistent. Seasonal ammonia removal trends were observed within the wetland treatment cells. Among the plug flow cells, very little to no removal was observed in the winter, while approximately 60 percent or more of the influent ammonia concentration was observed to be removed in the summer.

The performance of the overland flow/plug flow cells was superior year-round, with greater ammonia removal in each season than any other cell. The seasonal pattern of ammonia removal within the wetland cells is controlled by the nitrification processes, which are limited by water temperature and dissolved oxygen concentrations. The further reduction of nitrate-nitrogen concentrations to less than 0.1 mg/I.. during the summer, is a likely indicator that denitrification plays a significant role in wetlands treatment performance. An average concentration removal rate of 22 percent total phosphorous was observed.

Sediment Quality

Wetland sediments at the SCWDP were monitored for changes in trace metal content. Because sediments function as a sink for trace metals, their accumulation can eventually result in toxic conditions to aquatic organisms. The principal sediment sampling studies included core sampling in vegetated areas, a sediment partitioning study, and an accretion study.

Three layers of vertical stratification of wetland sediments were identified through the partitioning study. The top sediment layer consisted of the loosely structured detrital matter at the sediment-water interface. The two lower layers consisted of a fairly well consolidated vegetative mat and the clay soils underlying this mat. The three sediment layers were characterized by average percent solids concentrations of approximately 3, 50, and 73, respectively.

Analysis of the sediment trace metals data indicated an apparent trend towards increasing sediment concentrations over time for arsenic, chromium, copper, nickel, and zinc. For the other trace metals monitored (silver, cadmium, mercury and lead) no consistent observable trend towards increasing sediment concentrations was observed.

Analysis of wetland sediment samples indicated an apparent trend toward elevated trace metals concentrations within the inlet end of the wetland. However, there were no statistically significant differences observed between metals concentrations at the inlet and outlet ends of the wetland. Chromium and nickel were the only metals for which sediment metals concentrations appeared to increase over distance.

Detrital layer trace metals concentrations were on average four times greater than the underlying mat and clay layers, a trend that was statistically significant for all metals but chromium and nickel. Of the five trace metals whose sediment concentrations increased over time, only chromium and nickel were observed in concentrations approaching or exceeding the NOAA PELs.

Metals Concentrations in Wetland Vegetation and Biota

Wetland vegetation was sampled each year and analyzed for metals and nutrients. *Scirpus* rhizome metals concentrations were found to be twice as great as those observed in *Scirpus* shoots. Metals concentrations in treatment wetland vegetation generally exceed both control cell and Laguna Creek vegetation concentrations. Vegetation metals concentrations did not appear to increase over time.

Tissue samples from fish residing in the treatment wetlands were collected and analyzed for their metals content from 1995 to 1998. Control samples were also taken directly from fish in the supply truck used to deliver the stocked fish. In general, the concentrations of trace metals in fish tissue samples from the wetlands were not significantly different from the concentrations found in control fish samples.

Invertebrate tissue samples were also collected and analyzed for their metals content. In general, the concentrations of metals in invertebrate tissue were similar among the treatment wetland cells, habitat cell, and Laguna Creek. In an earlier study, species with low pollution tolerance scores were observed in both the wetland and creek communities.

FATE OF TRACE METALS

Nine trace metals (silver, arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc) were consistently monitored in the wetland water column, sediment, vegetation and biota over the five-year project. These trace metal observations were analyzed to identify their fate within the treatment wetlands. The trace metal observations have also been used to calibrate a trace metal transport model developed by the SRCSD.

Observations and Analysis of Fate of Trace Metals

Sources of trace metals to the wetlands include the secondary wastewater applied and atmospheric deposition. Paths for trace metals to leave the wetlands include surface outflow, infiltration to groundwater, plant harvest, and volatilization to the atmosphere. Additionally, trace metals can accumulate within wetland vegetation (above and below-ground), biota, and within wetland sediments

Accumulation in the sediment appears to be the dominant pathway for trace metals, exceeding fifty percent for most metals. Loss in the effluent was the next largest pathway for incoming metals. Infiltration of metals to groundwater and accumulation of metals in plant roots ranged between 5 and 20 percent of the influent metal mass. Very little of the incoming trace metals were found to accumulate in standing vegetation or leave via vegetation harvesting, regardless of the metal.

CWFATE Model

A mathematical model, the Constructed Wetland Fate And Aquatic Transport Evaluation (CWFATE) model, was developed for the SRCSD. The general organizing concept for the CWFATE model was an accounting of the water balance and mass budgets for influent nutrients (carbon and nitrogen) and metals within the water, sediment and biomass components of the constructed wetland. Calibration of the CWFATE model with the five-year SCWDP results will be presented in a separate document.

WETLAND MANAGEMENT METHODS

The development and evaluation of constructed wetlands management procedures was a primary objective of the demonstration program. Hydraulic, vegetation, vector and habitat management procedures were tested and are summarized below.

Hydraulic Management

The movement of water is a controlling factor in the performance of treatment wetlands. Hydraulic factors influenced by design include the hydraulic detention time, flow paths, and hydraulic distribution mechanisms. Operational controls are available in the form of pumps, valves and weirs. Analysis of wetland hydraulics at the SCWDP included a water balance, tracer studies and friction surveys.

The treatment wetlands received an average daily flow of 1.0 Mgal/d of disinfected secondary effluent that was split among the ten treatment cells. A typical treatment wetland cell was operated to provide an average influent flow rate of 70 gal/mm and to maintain a 1.5-ft water depth within the vegetated section of the cell by control of the effluent weir. After rainfall additions and losses to evaporation, transpiration, and infiltration, the wetland cells produced an average effluent flow rate of approximately 60 gal/mm.

Flow monitoring was accomplished using propeller meters installed on inlet manifolds, v-notch weirs, and ultrasonic depth meters on the effluent weirs, and daily on-site measurements of precipitation and evaporation. Several tests to measure infiltration were made in a number of the wetland cells.

Large discrepancies were observed between measured wetland inflows (inf1uent flow plus precipitation) and outflows (sum of effluent flow, evapotranspiration and infiltration). Although some of this discrepancy may be attributed to underestimated evapotranspiration, it is considered to be primarily due faulty inflow and outflow measuring devices. Precipitation and infiltration measurements were considered to be reliable.

Based on a modified water balance, the difference between inflow and outflow was 12 percent of influent flow on an annual basis. Precipitation added approximately 3 percent of influent flow to the wetland cells on an annual basis, while evapotranspiration and infiltration removed approximately 5 and 10 percent of the influent flow from the wetland on an annual basis, respectively. Water losses ranged from a high of 20 percent in the summer to a low of 2 percent in the winter.

The hydraulic residence time for the, typical wetland treatment cell, as determined from lithium-chloride tracer tests conducted over three consecutive years, ranged from 9 to 12 days.

Although typically described as plug-flow, the tracer analyses indicated that partial mixing due to dispersion, relative dead flow regions and short-circuiting all occur in the treatment wetlands.

Surveys of water elevations and ground surfaces were performed in 1997 to identify the frictional characteristics of flow in the treatment wetlands under a range of flowrates and vegetation densities. Observed values of Manning's n ranged from 3.6 to 14.6 s/m^{1}Q The values calculated from the SCWDP are significantly higher than typical values reported for natural open channels, but are similar to values reported for densely vegetated treatment wetlands. The head loss over the treatment cell was observed to range from 0.3 to 3 in for various flowrates.

Vegetation Management

The presence of vegetation, and associated dead, decaying and detrital material, in the wetland can have numerous impacts on wetland processes, including the hydraulic and water quality performance of wetland cells as well as the efficiency of vector control measures.

A number of different techniques were used for vegetation management over the five-year project. Combing, thatching and channelization were all performed to: 1) provide better access for fish populations to all parts of the cell, 2) decrease harborage and overwintering habitat for mosquitoes, and 3) aid the effectiveness of larvacide applications by improving contact with the water surface. Vegetation was harvested from most of the wetland cells once a year in 1995 through 1997. No vegetation harvest was conducted in 1998 and Cells 5 and 7 were never harvested. Cell 8 was replanted in 1997 with *Scirpus californicus*.

Cell 9 was modified to have an open water:vegetated area ratio of 1:1 by creating alternating sections of open water and emergent marsh every fifty feet. Although only operated in this fashion for the final year of the project, no differences were observed in effluent water quality in comparison with the other wetland cells.

Vegetation in the wetland cells was dominated by two tall emergent macrophytes: *Scirpus acutus* and *Typha*. A study conducted in the habitat cell indicated the dominance of *Scirpus acutus* in water depths from 12 to 16 in, the presence of Scirpus cal~fornicus primarily in water greater than two feet, and the presence of *Typha* primarily in depths less than 8 in and greater than 2.3 ft. These observations were confirmed in the treatment cells where *Scirpus acuzus* populations have remained relatively consistent from year to year, whereas *Typha* populations within all areas, but the cell margin, declined.

The above ground vegetation biomass observed in a typical treatment cell was approximately twice the biomass observed in the groundwater supplied control cell. This difference in biomass density is indicative of the impact of nutrient-enriched wastewater on vegetation growth. An opposite trend was observed at the conclusion of the five-year project in the below-ground biomass; below-ground biomass in the control cell was healthier and over twice as dense as that observed in the treatment cells.

Vector and Pest Control

Because of the potential public health threat of mosquito-borne disease transmission, the monitoring and management of the mosquito larvae population was an essential component of the SCWDP. Mosquito larvae monitoring and control was conducted at the demonstration wetlands in coordination with the Sacramento-Yolo Mosquito and Vector Control District (SYMVCD). Weekly monitoring was conducted between March and October of each year. Mosquito larvae collected from random dips were sorted by growth stage and keyed to the genus or genus species level. A threshold limit of an average 0.1 *Culex* larvae per dip was used to trigger active vector controls. This threshold limit is typically applied near residential areas.

Mosquito control measures evaluated over the five-year program included vegetation management, biological larvacide applications, stocking of mosquito predators, and nightly overhead sprinkler application.

In 1994, prior to regular applications of biological larvacide, mosquito counts within the wetlands averaged 1.98 larvae per dip. The average count when biological larvacide was applied from 1995 through 1998 was 0.34 *Cuiex* larvae per dip.

The habitat cell and the control cell counts rarely exceeded the threshold level (<0.1 *Culex* larvae per dip). Mosquito counts in the influent half-cells consistently exceeded those in the effluent half cells. It is conjectured that elevated water temperatures, nutrient content, or vegetation density contributed to this phenomenon.

During the initial study season, Bti (*Bacillus thuringensis var. israelensis*) was applied with a backpack sprayer. A tractor-mounted spray system was later developed to apply liquid Bti with a large water volume to improve penetration of larvacide within the vegetation canopy. Due to the increasing number of Bti treatments required to maintain the threshold limit, larvacide applications were converted entirely to Bs (*Bacillus sphaericus*) beginning in 1997. Bs proved to be more effective than Bti due to its greater residual activity and improved application efficiency due to use of a granular material.

The treatment wetlands were stocked with mosquitofish (*Gambusia affinis*) and guppies (*Poecilia reticulata*) to aid in mosquito control. Although many fish survived the winters, the populations were stocked annually to maintain a density of approximately one fish per square foot. Mosquitofish were not singularly sufficient to maintain target larvae threshold levels. No other form of natural mosquito predation was studied. The overhead sprinkler experiment conducted in 1995 was successful at suppressing oviposition, but was discontinued due to cost inefficiencies associated with the pilot project. No adult mosquito problems resulted from the demonstration.

The population of muskrats (*Ondatra zibethicus*) within the treatment wetlands increased over the course of the project to between 200 and 400 animals. The burrowing activities of this population resulted in considerable damage to the wetland berms. A live-trapping and relocation program dramatically reduced the population.

Habitat Management

Although habitat creation was not the focus of the SCWDP, the treatment wetlands appeared to thrive biologically during the course of the project. Efforts to create and enhance habitat at the SCWDP included the construction of barn owl boxes and raptor perches, and timing all vegetation harvesting activities after nesting seasons. No adverse effects (acute or chronic) were reported among observations of treatment wetland flora and fauna.

Investigation of the macroinvertebrate communities among treatment cells indicated a greater abundance and higher diversity within the groundwater-supplied control cell, although pollution tolerance appeared to be similar among all treatment cells. Greater abundance and diversity was observed in the samples of macroinvertebrates taken from treatment cells than in Laguna Creek samples.

A total of 98 bird species, including nine California Species of Concern and 18 confirmed nesting species, were observed at the constructed wetlands and the immediately surrounding environs. When compared to a nearby natural wetland, the emergent marsh habitat at the SCWDP contained higher densities for six of fifteen wetland dependent bird species.

MAJOR PROJECT FINDINGS

Major findings identified during the course of the five-year study include:

Water Quality

I. A decrease in average wetland temperatures was observed in eleven months of the year, with an annual average temperature reduction of 3 ^{0}C.

II. The treatment wetlands demonstrated a 55 percent likelihood of compliance with a 10/10 BOD_5/TSS limit and a 93 percent likelihood of compliance with a 30/30 BOD_5/TSS limit.

III. Seasonal ammonia removal trends were observed with little to no removal observed in the winter and 60 percent concentration reduction observed in the summer. The wetland cells with an overland flow section achieved superior year-round performance, with greater ammonia removal in each season than any other cell.

IV. Three metals; zinc, copper and nickel, accounted for 90 percent of the annual average 11.2 lb/ac-yr mass loading of metals in the secondary effluent applied to the treatment wetlands.

V. Comparison of effluent total metals concentrations with the ambient water quality criteria found in the 1997 draft of the California Toxics Rule indicates complete compliance.

VI. Mass removal rates for six metals (silver, cadmium, copper, mercury, lead and zinc) consistently exceeded 60 percent. No differences were found in metals removal between the treatment cells.

VII. Concentration and mass removal rates for three trace metals (arsenic, chromium and nickel) steadily declined over the study. The cause of their decreased removal performance is likely related to their presence in the wetland in a predominantly soluble form and a chemistry that inhibits their removal from solution.

VIII. Water column speciation investigations indicated strong organically-complexed nickel that is resistant to removal, weak organically-complexed copper that underwent significant reduction in concentration upon passage through the treatment wetland and a sixty percent reduction in hexavalent chromium concentration despite little apparent removal of total chromium concentrations.

Sediment Quality

I. Three vertically stratified sediment layers were identified characterized with average percent solids concentrations of approximately 3, 50, and 73, respectively.

II. Based on the sediment trace metals data, an apparent trend towards increasing sediment concentrations over time was found for arsenic, chromium, copper, nickel, and zinc. For the other trace metals (silver, cadmium, mercury and lead) no consistent observable trend towards increasing sediment concentrations was observed.

III. Wetland sediment metals concentration remained well below EPA Part 503 biosolids limits and California TTLC toxicity standards.

IV. Analysis of wetland sediment samples indicated an apparent trend toward elevated trace metals concentrations within the inlet-side of the wetland cells. However, there was no statistically significant difference observed between the inlet and outlet ends.

V. Detrital layer trace metals concentrations were on average, four times greater than the underlying mat and clay layers, a trend that was statistically significant for all metals, but chromium and nickel.

VI. Of the five trace metals that increased in concentration in the sediment over the study, only chromium and nickel were observed at levels approaching or exceeding the freshwater sediment Probable Effect Levels.

VII. Accumulation in the sediment appears to be the dominant removal pathway for trace metals, averaging 53 percent of the influent metals mass for most metals.

Vegetation and Biota

I. Vegetation in the wetland cells was dominated by two tall emergent macrophytes: *Scirpus acutus* and *Typha*.

H. Above ground vegetation biomass was observed to increase over the initial three years and appeared to level off at an average of 11 dry tons per acre for the final project years. The above ground vegetation biomass observed in a typical treatment cell was approximately twice that observed in the groundwater supplied control cell.

m. Rhizome metals concentrations were found to be twice as great as those observed in shoots.

IV. Vegetation metals concentrations did not appear to increase over time.

V. Above ground standing vegetation and harvested vegetation each accounted for less than one percent of the influent metal mass.

VI. In general, the concentrations of trace metals in samples of fish tissue and invertebrates from the treatment wetlands were similar to the concentrations found in the control wetland.

VII. A greater abundance and diversity were observed in the samples of macroinvertebrates taken from the treatment cells as compared to samples from nearby Laguna Creek.

Hydraulic Monitoring

I. The difference between inflow and outflow on an annual basis was 12 percent based on the influent flow. Precipitation added approximately 3 percent of influent flow to the wetland cells on an annual basis, while evapotranspiration and infiltration removed approximately 5 and 10 percent of influent flow from the wetland on an annual basis, respectively.

II. The average hydraulic residence time for the typical wetland treatment cell ranged from 9 to 12 days. Lithium chloride tracer studies conducted at the wetland did not produce results consistent with plug flow reactors or complete mix reactors in series.

It is hypothesized that the discrepancy of the wetland data with these flow models can be attributed to the edge effects of the wetland.

III. Observed values of Manning's n were significantly higher than typical values reported for natural open channels, but are similar to values reported for densely vegetated treatment wetlands.

Wetland Management

I. Although the SCWDP was not managed actively to enhance habitat, the treatment wetlands appeared to thrive biologically during the course of the project. No adverse effects (acute or chronic) were reported among observations of treatment wetland flora and fauna.

II. A total of 98 bird species, including nine California Species of Concern and 18 confirmed nesting species, were observed at the constructed wetlands and the immediately surrounding environs.

III. The treatment wetlands were stocked with mosquitofish (*Gambusia affinis*) and guppies (*Poecilia reticulata*) to aid in mosquito control, however, the fish were determined not to be singularly sufficient to maintain target mosquito larvae threshold levels. No other form of natural mosquito predation was studied. No adult mosquito problems developed over 5 years.

IV. Bs (*Bacillus sphaericus*) proved to be more effective than Bti (*Bacillus thuringensis var. israelensis*) due to its residual activity, improved application efficiency, and reduced application cost.

V. The population of muskrats (*Ondatra zibethicus*) within the treatment wetlands increased over the course of the project to between 200 and 400 animals. The burrowing activities of the muskrats caused significant damage to the wetland berms. A live-trapping and relocation program helped dramatically reduce the resident muskrat population.