The San Francisco Bay Constructed Wetland Treatment System

The Use of Constructed Wetland Treatment Systems for the Removal of Toxic Trace Elements from Electric Utility Wastewater: Role of Vegetation

Technical Report

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REPORT SUMMARY

Biological volatilization of Selenium (Se) is attractive as a remediation strategy since it results in a permanent loss of Se through gaseous dissipation to the atmosphere. Furthermore, volatile forms of Se are considerably less toxic and Se may be redeposited in areas deficient in this trace element. This report summarizes the findings of a research project investigating the role of Se volatilization in Se removal by the San Francisco Bay wetland.

Background

In 1988, the Chevron oil refinery in Point Richmond, California established a 36-hectare surface flow constructed wetland on the San Francisco Bay, primarily as a restoration project. Early testing of the wetland waters indicated that overall water quality improved dramatically after passage through the wetland, and that Se was reduced by approximately 70% (Duda, 1992). Although Se levels in the effluent entering the wetland were well below permit requirements, there remained concern that Se retained by the wetland might increase to concentrations that could eventually harm wildlife. This concern led to a field study to determine the amount of Se partitioned to the sediments, waters and plant material. This inventory could account for only 50 to 70% of the Se removed by the wetland (Duda, 1992). The fate of the remainder of the removed Se was unknown. One possible explanation for the ‘missing Se’ is that plants and microbes converted it to a volatile form that then dissipated to the atmosphere. The environmental significance of Se volatilization at the San Francisco Bay wetland was unknown. The goal of this study was to determine if volatilization represented a substantial component of Se removal by wetlands.

Objectives

- To determine the rate of Se volatilization at the San Francisco Bay wetland and if it changes significantly over time.
- To determine if there are differences in Se volatilization rates between the dominant plant systems which currently populate the wetland.
- To determine if there are correlations between Se volatilization rates and available Se, Se concentrations in plant tissues, and environmental parameters such as pH.
- To estimate the percentage of volatilization in terms of the Se mass-balance in the wetland.

Approach

The project team made two separate sets of Se volatilization measurements in Pass 1 of the San Francisco Bay wetland using a chamber and trap system. Concomitant with these measurements, they also sampled inlet, outlet, and pore waters, sediments, and plant tissues from dominant species in the wetland, along with physicochemical monitoring of the water. They returned all samples to the laboratory for chemical analysis.

Results

Mean rates of Se volatilization in Pass 1 ranged from 10 - 190 $\mu g\ m^{-2}\ d^{-1}$. Assuming these same rates are the mean volatilization rate for the entire wetland, the percent of Se removed by volatilization ranges between 2 - 44%. Manipulation experiments (e.g., shoot removal) successfully increased Se volatilization rates up to 4-fold. The research team found relationships between volatilization rates and measured environmental parameters in several instances.

The entire wetland removed 89.1 ± 0.6% of inlet Se (mass). Pass 1 removed most of the Se, including 67 ± 2.8% of inlet Se (mass). The entire wetland removed between 60 - 230 grams Se per day. Chemical analyses determined that the mean total Se concentration in inlet waters was 25.8 ± 5 $\mu g\ L^{-1}$, and 8.0 ± 3.2 $\mu g\ L^{-1}$ in Pass 1 outlet waters. The mean total Se concentration in Pass 3 outlet waters was 4.5 ± 0.6 $\mu g\ L^{-1}$. The mean Se concentration in pore-water at the study site was 6.4 $\mu g\ L^{-1}$, and 6.8 $mg\ L^{-1}$ in pooled plant shoot tissue. The mean Se concentration in pooled plant root tissue was 16.4 $mg\ L^{-1}$. The mean Se concentration in soil (top 10 cm) at the study site was 4.3 $mg\ L^{-1}$.

EPRI Perspective

The results presented in this report show that the San Francisco Bay wetland is highly effective in removing Se from refinery wastewater. High rates of Se volatilization are present in the San Francisco Bay wetland over vegetated and non-vegetated sites. The report discusses the potential for increasing the extent of Se removal through volatilization by wetland management practices. A long-term Se volatilization study across the entire wetland would be useful to increase the understanding of Se volatilization at the San Francisco Bay wetland, and other wetlands.

Keywords

Constructed wetlands
Selenium volatilization
Effluent treatment

ABSTRACT

The San Francisco Bay constructed wetland in Richmond, CA, was constructed in 1988. This 36-hectare, surface flow constructed wetland is used to improve the quality of wastewater from the Chevron oil refinery for approximately six months each year (April - September). Treated wastewater from the refinery enters the wetland into Pass 1, and then flows into two other nearly equally large sections before flowing into San Francisco Bay. The mean total selenium (Se) concentrations in inlet water and Pass 3 outlet water were 25.8 ± 5 μg L^{-1} and 4.5 ± 0.6 μg L^{-1}, respectively. This translates to a 89% mass Se removal by the wetland. Rates of Se volatilization, mass loading and removal were measured in the San Francisco Bay wetland to investigate the role of Se volatilization in terms of the overall Se mass balance. Mean rates of Se volatilization in Pass 1 ranged from 10 - 190 μg m^{-2} d^{-1}. If these same rates are assumed to be the mean volatilization rate for the entire wetland, the percent of Se removed by volatilization ranges between 2 - 44%. In addition, manipulation experiments (e.g., shoot removal) successfully increased volatilization rates (up to 4-fold), and relationships between volatilization rates and measured environmental parameters were found in several instances. The results presented in this report show that 1) the San Francisco Bay wetland is highly effective in removing Se from refinery wastewater; 2) high rates of Se volatilization are present in the San Francisco Bay wetland over vegetated and non-vegetated sites; 3) there is potential to increase the extent of Se removal through volatilization by wetland management practices; and 4) a long-term Se volatilization study across the entire wetland should be made.

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1

INTRODUCTION

1.1 The San Francisco Bay Constructed Wetland

Measurements of Se volatilization rates from different vegetated and non-vegetated sites in the Chevron Richmond Refinery Water Enhancement Wetland on the San Francisco Bay (San Francisco wetland), and sampling of sediments, sediment pore-water, plant tissues, and inlet and outlet waters were conducted to 1) investigate the role of volatilization in terms of selenium (Se) mass-balance, 2) identify possible differences between plant species in Se accumulation and volatilization, and 3) identify likely target areas for future research.

In 1988, the Chevron oil refinery, Point Richmond, California, established a 36-hectare surface flow constructed wetland, primarily as a restoration project. Early testing of the wetland waters indicated that overall water quality was dramatically improved after passage through the wetland, and that Se was reduced by approximately 70% (Duda, 1992). Although Se levels in the effluent entering the wetland were well below permit requirements, there remained a concern that Se retained by the wetland may increase to concentrations that eventually could be harmful to wildlife. This concern led to a field study to determine the amount of Se partitioned to the sediments, waters and plant material. This inventory could only account for 50 to 70% of the Se removed by the wetland (Duda, 1992). The fate of the remainder of the Se removed was unknown.

One possible explanation for the “missing Se” is that it had been converted to volatile forms and had dissipated to the atmosphere. Biological volatilization of heavy metals (e.g., mercury) and metalloids (e.g., Se) has been known to occur for a number of years, in a variety of marine (Amouroux et al, 1994; Ben-Basset and Mayer, 1977) and terrestrial (Siegel and Siegel, 1987; Frankenburger and Karlson, 1994; Weres et al, 1989) environments. The actual environmental significance of volatilization; however, is not well known for any metal or metalloid.

Both plants (Terry et al, 1992) and microbes (Azaizeh et al, 1997; Frankenberger and Karlson, 1994) have been shown to transform various non-volatile forms of Se (-2, +4 and +6) to volatile forms such as dimethyl selenide (DMSe). Cooke and Bruland (1987) estimated that as much as 30% of the Se removed from drainage water moving through the Kesterson Reservoir system was volatilized. Allen (1991) also suggested that volatilization could represent a significant component of Se removal by wetlands. Prior to this study; however, there were no actual field measurements exist to support the view that volatilization represents a substantial component of Se removal by wetlands.

As a remediation strategy biological volatilization of Se is attractive because it results in a permanent loss through gaseous dissipation to the atmosphere. Furthermore, volatile forms of Se are considerably less toxic (Wilber, 1980; Ganther et al, 1966; McConnell and Portman, 1952). Volatile Se may be redeposited in areas deficient in this trace element (Haygarth et al., 1995; Atkinson et al., 1990), which is also an important nutrient (Mayland, 1994; National Academy of Sciences; 1989; Rotruck et al, 1973).

To date, only a few measurements of Se volatilization *in situ* have been made. Prior to the present study, no data were available to evaluate, or estimate, the significance of volatilization in the San Francisco Bay wetland. Since our laboratory is one of the few studying biological transformations of metals and metalloids (specifically Se), we were given the opportunity to apply our research to investigate the role of Se volatilization in the San Francisco Bay wetland. This report summarizes the findings of this project.

1.2 Project Goals

The project was designed to answer the following basic questions about Se volatilization in the San Francisco Bay wetland:

- Is Se volatilization occurring at measurable rates?
- Are there differences in volatilization rates between the dominant plant systems, which currently populate the marsh?
- Do volatilization rates change significantly over time?
- Are there correlation’s between Se volatilization rates and: available Se, plant Se concentration and environmental parameters such as pH?
- What is the best estimate of the percentage of volatilization in terms of the marsh Se mass-balance?

The work presented here was designed as a preliminary survey to answer basic questions about Se volatilization in the wetland. Research directed at determining the overall role of volatilization in terms of the Se mass-balance across the entire wetland would need to consider factors such a spatial and seasonal variation, which are beyond the scope of this initial investigation. Results from the present study will be used determine if a long-term, more comprehensive study should be made.

2
METHODS

2.1 The Study Site

The Chevron Richmond Refinery Water Enhancement Wetland is located near the mouth of the San Pablo Bay, adjacent to the San Francisco Bay (Fig 2-1). The 36-hectare, surface flow constructed wetland is used to improve the quality of wastewater for approximately six months each year (April - September). During the remainder of the year it is used for stormwater impoundment. The wetland is divided into three nearly equal sections, referred to as Passes 1, 2 and 3 (Figure 2-2). Treated wastewater from the refinery enters the wetland at the south-west corner of Pass 1 (“Inlet”, Figure 2-2), and flows down a 2-meter wide channel, which runs north between Passes 1 and 2. Inlet water is then distributed laterally in an easterly direction across Pass 1, and is collected in a canal, which transfers the water to Pass 2. Figure 2-2 shows the generalized flow of water through Passes 1, 2 and 3. Outlet water from the wetland is recombined with refinery waste water, and released to San Francisco Bay. The San Francisco Bay wetland has been used in this manner since 1991, with water flow rates ranging between 4.0 - 10.0 million liters per day.

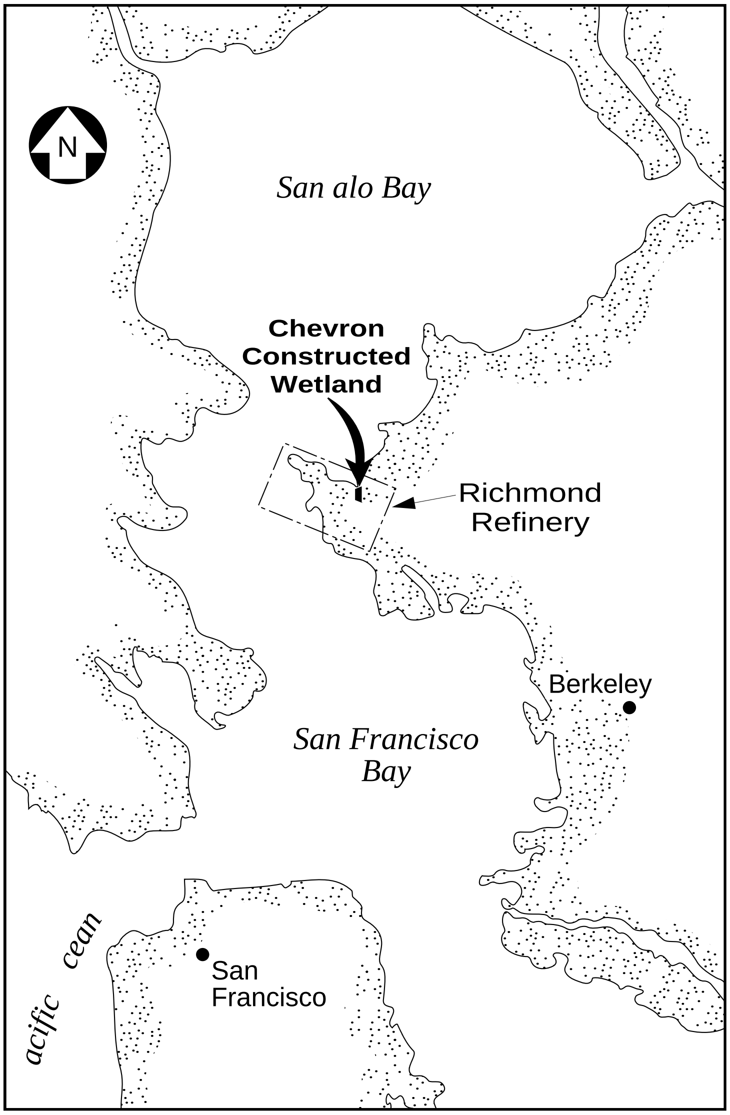

Figure 2-1
Location of the Chevron Richmond Refinery and the San Francisco Bay Constructed Wetland in Relation to San Francisco Bay

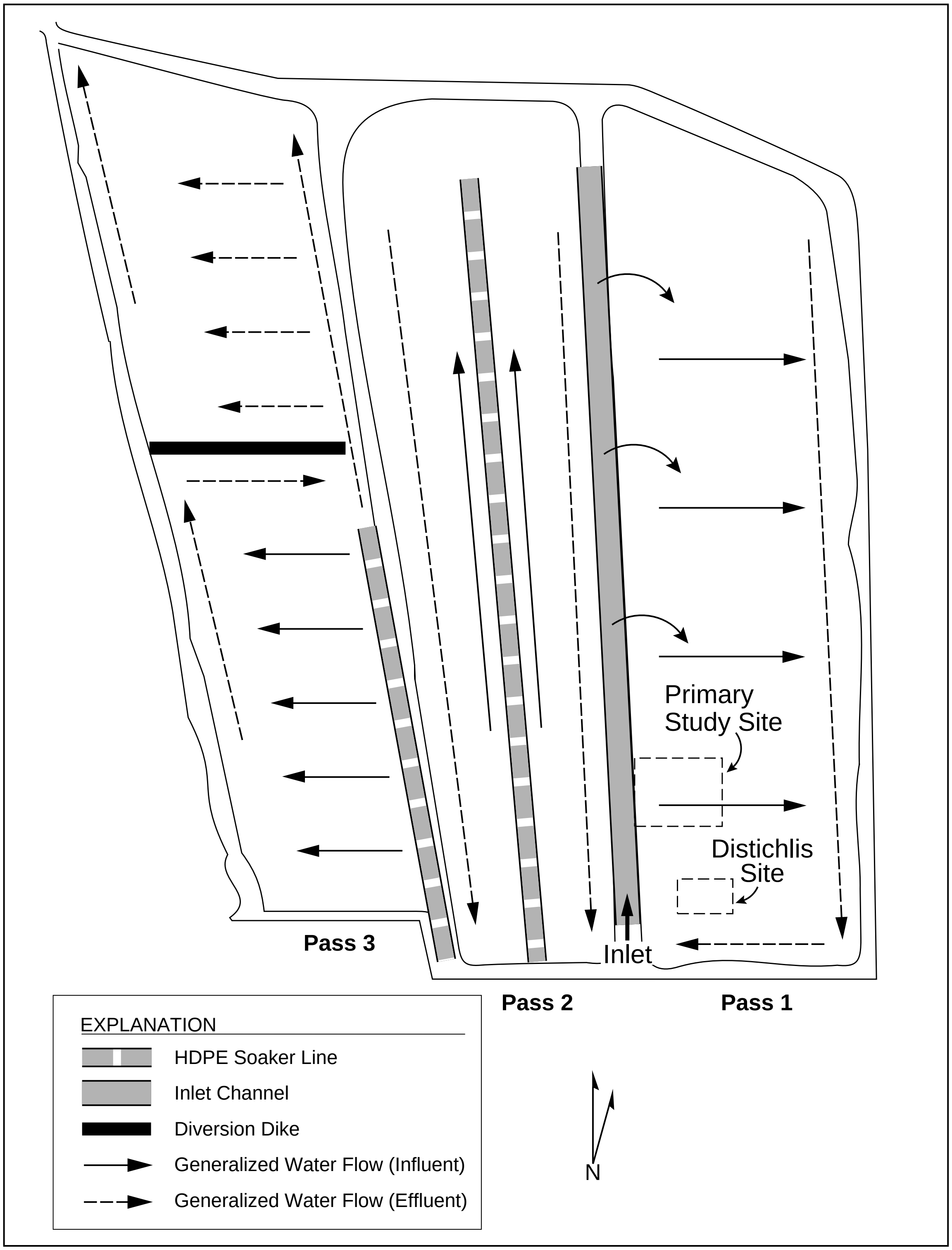

Figure 2-2
Schematic of the San Francisco Bay Wetland Showing Generalized Water Flow and Location of Study Sites

During the growing season, plant cover in Pass 1 is dense and is dominated by saltmarsh bulrush (*Scirpus maritimus* and *Scirpus robustus*) with cattails (*Typha angustafolia* , *Typha domingensis* and *Typha latifolia*) being the next most populous species. Pass 2 is primarily open-water; however stands of saltmarsh bulrush, cattails and tules (*Scirpus acutis* var *occidentalis* and *Scirpus californicus*) have become established at the southern end and now comprise 10 - 15 % of the area of Pass 2. The vegetation in Pass 3 is similar to Pass 1, however, plant stands tend smaller and coverage is not as thick as in Pass 1. Other plant species common to fresh-brackish water wetlands in the area have become established in various regions of the wetland, these include: brass buttons (*Cotula australis*), saltgrass (*Distichlis spicata*), and marsh gumweed (*Grindelia stricta* var *angustifolia*). The diversity of later-successional species; however, appears low compared to natural wetlands in the region (B. Ertter, pers. obs).

2.2 Experimental Design

Two separate sets of Se volatilization measurements are reported here. The first set of measurements (Set I, February 7 - April 18, 1995) were made to determine if Se volatilization rates varied from different vegetated and non-vegetated sites in Pass 1, and to select a site for a more intensive and systematic study (Set II measurements, outlined below). Set I volatilization measurements were considered preliminary because they were not made systematically (i.e., length of measurement and replication varied) and they were made before the air and electrical power systems were completed (i.e., chambers were not equipped with mixing fans; see below). The vegetated sites measured during Set I were: saltmarsh bulrush, cattails, brass buttons and rabbitfoot grass (*Polypogon monspeliensis*); non-vegetated sites included the inlet channel, fungal mats and bare soil. These measurements were made at selected sites across the entire southern half of Pass 1.

Set II volatilization measurements were made June 23 - October 13, 1995, and included systematic measurements of Se concentrations in sediments, plant tissues, sediment pore water and Pass 1 inlet and outlet waters. Because Pass 1 is nearly completely covered with vegetation during the growing season we decided to measure volatilization rates from the three most common plant species (saltmarsh bulrush, cattails and brass buttons) and two common minor plant species (saltgrass and rabbitfoot grass). In addition, volatilization rates were measured for the inlet channel and for saltmarsh bulrush sites that were manipulated by cutting off the shoots (detopped).

Set II measurements were made in an area measuring approximately 75 × 75 meters located in Pass 1 (Primary Study Site, Figure 2-2). This site was chosen because it was central to dense, monotypic stands of each of the chosen plant species. Saltgrass measurements were made in a different area measuring approximately 10 × 40 meters (saltgrass site, Figure 2-2), because saltgrass was established only near the southern end of Pass 1.

For Set II measurements, Se volatilization rates were monitored continuously for week-long periods. Six collection chambers (described below) were used to monitor volatilization rates from two different plant species (or the inlet channel) each week, using three replicate chambers for each measurement. Chambers were moved weekly to randomly selected sites within the study areas as follows. During the first week, three chambers were used to monitor volatilization rates for saltmarsh bulrush, and three chambers for saltgrass. The second week, the chambers were moved to monitor volatilization rates for brass buttons and the inlet channel. During the third week saltmarsh bulrush was again monitored, along with detopped saltmarsh bulrush sites. In the fourth week, the chambers were used to monitor sites populated with cattails and rabbitfoot grass. This sampling plan is summarized below:

Week 1	Week 2	Week 3	Week 4
saltmarsh bulrush	brass buttons	saltmarsh bulrush	cattails
saltgrass	inlet channel	detopped bulrush	rabbitfoot grass

This 4-week cycle was repeated four times during the 16-week period (6/23 - 10/13/95), with one exception. Saltmarsh bulrush was monitored every other day for two weeks using all six volatilization chambers (9/1 - 9/15/95). Hence, no Se volatilization measurements were made for cattails during the third 4-week period. We elected to build a higher-resolution data set for saltmarsh bulrush because it is the most common plant species found in the wetland.

2.3 Measurement of Se Volatilization

Before measurements it the wetland could begin it was necessary to develop a Se volatilization sampling method, which would be appropriate for long-term use in the wetland; no such methodology existed at the time. This work consisted of the design and construction of a Plexiglas volatilization chambers, which could accommodate both short and tall plant species, the design and construction of movable compressed-air and electrical systems to supply the volatilization chambers, and the development of a new Se trapping method and analytical protocol.

Volatile Se trap development

The volatile Se trapping and extraction protocols used here were adapted from Biggar and Jayaweera (1993) and Jayaweera and Biggar (1992). Before field measurements began, charcoal trap thickness and flow rate were optimized in the laboratory using 10.0 cm diameter discs of filter material in Se standard-recovery experiments. Using parameters established from this work, near 100% recovery of small (5.0 µL) and large (25.0 µL) aliquots of dimethylselenide (DMSe) standard, was repeatable in greenhouse experiments using a chamber equal in dimensions to the field chambers. These parameters: twenty 10.0 cm diameter discs (approximate mass = 70.0 grams) used with an air-flow rate of 6.6 L min^{-1}, were then used for making field measurements. Various extraction procedures were also compared, resulting in the analytical procedure described below and in Appendix B.

Chamber description

Collection chambers were constructed as open-bottom cubes measuring 90.0 cm on each side. Chamber inlet and outlet ports were made of 10.0 cm wide × 25.0 cm tall Plexiglas cylinders. Inlet ports were open to the atmosphere on top of the chambers (except for a small rain shield), and were connected inside the chamber to a length of 4.0 cm diameter tubing, which transmitted scrubbed inlet air to the bottom of the collection chambers. The chamber outlet ports were sealed to the outside atmosphere and each was connected to a vacuum supply and regulator to ensure that the flow of air through each chamber was the same. Air-flow through each chamber provided one complete exchange approximately every 1.9 hours (3.8 hours for cattail chambers, see below). To ensure that air inside the chambers was well mixed, the chambers were fitted with 12 volt (DC) mixing fans, which were rated to move approximately 3.0 m^3 air min^{-1}. For cattail measurements, extra chamber modules were stacked together, which increased the chamber height to 180 cm. Two separate gaskets were used on all chamber connections to ensure against leaks. The tops of the chambers were covered in shade cloth for Set II measurements to minimize heat build-up inside the chambers.

Temperature inside and outside one of the chambers at mean plant height was monitored continuously throughout Set II measurements using two temperature data loggers (Hobo XT; Onset Instruments, Pocasset, MA). Analysis of the temperature data from the study period showed that mean daily temperature inside the chambers was 22.4 ± 3.3°C (mean 6 standard deviation) and the mean daily temperature outside the chambers was 18.7 ± 2.1°C. The difference between inside and outside temperatures was 3.75 ± 1.76°C (mean ± standard error).

Field trapping methodology overview/quantification of Se-fluxes

Rates of Se volatilization were measured *in situ* using open-bottom Plexiglas collection chambers (described above) to cover selected sites, inserting the bottom edges of the chambers 0 to 5 cm into the sediments. Each chamber measured 0.81 $meter^2$ in basal dimension. Great care was taken to ensure that the bottoms of the chambers were adequately sealed with the sediments, and to minimize disturbance to the sites. Inlet and outlet ports, located on top of the chambers, held activated charcoal filter material (Booda Products, Calabasas, CA) for trapping volatile Se (described above). A vacuum applied to the outlet port caused ambient air to be drawn into the chamber. As a result, the chamber inlet filter served to scrub the incoming air of ambient volatile Se, and the outlet filter trapped volatile Se emitted from within the collection chamber. Volatilization rates then, were calculated as the mass of Se trapped in the outlet filter, divided by the collection time and per surface area of the collection chamber (expressed as: µg Se volatilized m^{-2} d^{-1}).

Volatile Se trap extraction and analysis

After being exposed in the field, volatilization traps were carefully removed from the chambers and placed in sealed plastic bags for transport to the lab. Charcoal traps were changed once per week for the first four weeks of Set II measurements, then two times per week for the remaining twelve weeks. Within 2 hours after being removed from the field, the total weight of the volatilization trap was recorded, then a 1/4 sub-sample of each disc was carefully cut, and the weight of the entire sub-sample was recorded. The sub-sample was then immediately placed in a Nalgene bottle with extraction solution, which consisted of: 160 mL of 0.05 M NaOH and 40 mL of 30% H_2O_2. The caps of the bottles were slightly loosened for 24 hours, to prevent pressure build-up. Samples were prepared for analysis by heating a 500 µL sample of extraction solution with 500 µL 30% H_2O_2 at 91°C for 25 minutes. After cooling, 5.0 mL of concentrated HCl was added to the samples, which were heated again at 91°C for 25 minutes. Samples were then diluted to a 10 mL final volume with distilled deionized water. Samples of charcoal material that had not been exposed in the field were extracted and prepared for each analysis. No Se was detectable in these matrix blanks.

2.4 Water, Sediment and Plant Tissue Se Determinations

Samples of soil pore water, sediments and plant tissues were collected from each volatilization chamber location during sampling trips, which were made mid-week during each week of Set II measurements, and every other day for the two-week monitoring period described above. Samples of Pass 1 inlet and outlet waters were also collected during each sampling trip.

Pass 1 inlet and outlet, and Pass 3 outlet waters were also sampled weekly during the study period by the EPA-certified Chevron Chemical Company laboratory (Richmond, CA.). Chevron sampling and analytical procedures were according to EPA Method #270.3, which measures total Se (dissolved and particulate-bound forms). Chevron water concentrations are reported as µg total Se L^{-1}.

All UC Berkeley water samples were made using Rhizon soil-water samplers (pore size = 0.1 µm) with 10.0 mL Vacutainers. UC Berkeley water Se concentrations are reported as total dissolved Se (µg dissolved Se L^{-1}). First pass inlet and outlet waters were sampled horizontally from a 10.0 cm depth. Soil pore-water was sampled vertically along a 0 to 10 cm depth, directly adjacent to the volatilization chambers. The Rhizon samplers were carefully washed and flushed with deionized water and then were air-dried in-between uses.

Water chemistry measurements for all water samples were made immediately in the field. Sample pH was determined with a gel-filled combination electrode (Fisher Scientific, Pittsburgh, PA); electrical conductivity (EC) was determined with a hand-held conductivity meter (Model CDH-80MS, Omega Engineering, Stamford, CT), and redox potential (Eh) was determined with a combination platinum-reference electrode (Ag-AgCl) (Fisher Scientific, Pittsburgh, PA). Water samples were then brought back to the lab and were stored at -80°C until the end of the experiment for Se analysis.

Total dissolved selenium (µg Se L^{-1}) in water samples was determined by heating 2.25 ml sample with 0.5 ml 2% ammonium persulfate at 95°C for 25 minutes. Then, 2.25 ml concentrated HCl was added, and the sample was again heated at 95°C for 25 minutes. After cooling, sample volumes were adjusted with deionized water. This procedure was adapted from Weres et al (1989). Total dissolved selenite (µg Se IV L^{-1}) was determined by introducing the sample directly into the hydride generator.

Sediments were sampled from each chamber location during the first four weeks and last month’s four weeks of the Set II measurements. A hand auger was used to sample sediments from 0 - 10 cm. Fresh samples were brought to the lab where they were dried, cleaned of large organic matter, milled and stored for analysis at the end of the project. Soil samples were prepared for analysis with an acid digest procedure, according to Zawislanski and Zavarin (1996). This procedure is designed to liberate all forms of Se, values are reported as total Se (mg Se kg^{-1} dry weight).

Several plant samples were removed from near each volatilization chamber during each sampling trip. Plant samples were immediately brought back to the lab where shoot and root tissues were cleaned, rinsed with deionized water and separated. Plant samples were dried at 70°C. Whole shoot and root samples were then ground and mixed to ensure sample homogenization.

Plant-tissue samples were prepared for analysis using a nitric acid/hydrogen peroxide digestion procedure according to Martin et al (1975). Plant-tissue Se is reported as total Se (mg Se kg^{-1} dry weight).

The analytic protocols used to prepare volatilization, water, plant tissue and soil samples are given in Appendix B. All Se concentrations reported here were determined by hydride-generation atomic absorption spectroscopy using a Perkin-Elmer atomic absorption spectrophotometer (Model # 2280), equipped with a Varian hydride-generator (Model # VGA-76). Two sub-samples were prepared for analysis from each prepared field sample; Se concentration values were recorded as the average of these two determinations.

3
RESULTS AND DISCUSSION

3.1 Set I Se Volatilization Measurements

The results of Set I volatilization measurements are shown on Figure 3-1 (A) for vegetated sites, and Figure 3-1(B) non-vegetated sites. These data are also shown in Table 3-1. The values shown on Figures 3-1(A & B) were pooled from survey measurements (see Methods), so statistical comparison of these data is limited. A t-test showed that the mean volatilization rates for both saltmarsh bulrush and cattail measured in mid-February (149 ± 37, and 179 ± 101, µg Se m^{-2} d^{-1}, respectively) were significantly higher ($p<0.001$ and $p<0.01$) than rates measured for these same species in mid-March and mid-April (26 ± 18 and 21 ± 19 µg Se m^{-2} d^{-1}, respectively). The difference between the two groups of volatilization measurements made for rabbitfoot grass was not significant because of one low measurement made during 3/28 - 4/4 (29 µg Se m^{-2} d^{-1}).

Table 3-2 shows pooled mean values, and individual maximum and minimum measurements for the Set I volatilization measurements. The highest pooled mean volatilization rate and the highest individual measurement from vegetated sites for Set I measurements were from rabbitfoot grass: 115 ± 129 and 332 µg Se m^{-2} d^{-1}. The highest volatilization rate for non-vegetated sites, during Set I measurements, was a single measurement made over the inlet channel (206 µg Se m^{-2} d^{-1}; Figure 3-1(B)). The volatilization rates for wet and dry fungal mats (108 ± 61 and 46 ± 13 µg Se m^{-2} d^{-1}, respectively) were not comparable because of the small sample size for each measurement (n=2).

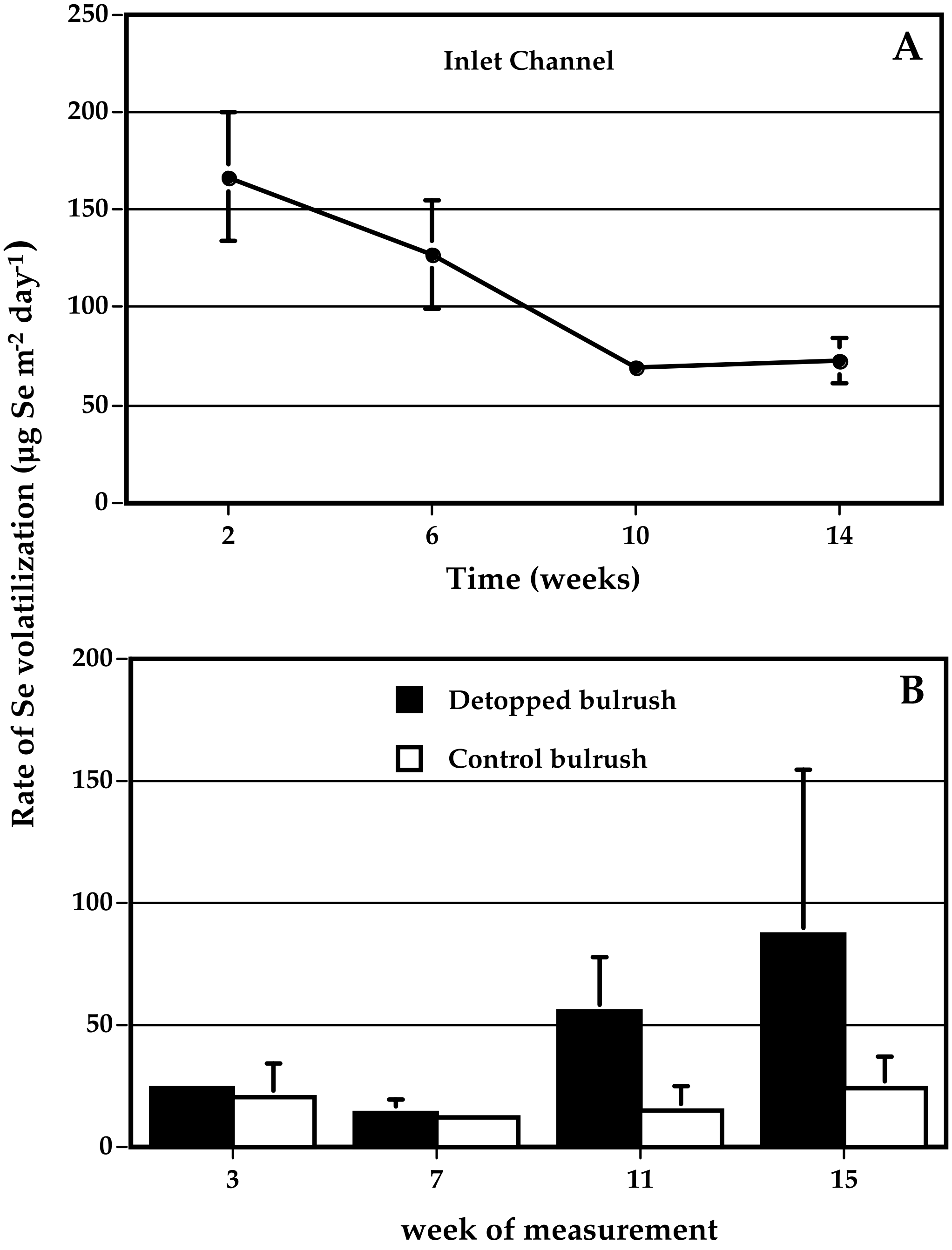

Figure 3-1
Results of Set I Se Volatilization Measurements (2/7 - 4/18/95, See Methods) From Various Vegetated (A), and Non-Vegetated (B), Sites in Pass 1 of the San Francisco Bay Wetland

Rates of Se volatilization = µg Se m^{-2} d^{-1} (mean ± standard deviation); (n)=number of measurements; unshaded bar indicates a different series of measurements made at the same, or similar, sites).

Table 3-1
Results of Set I Se Volatilization Measurements (2/7 - 4/18/95, See Methods) From Various Vegetated and Non-Vegetated Sites in Pass 1 of the Chevron Wetland

Rates of Se volatilization = μg Se m^{-2} d^{-1} (mean ± standard deviation);
(n) = number of measurements.

Site Measured	Dates	n	Mean Volatilization Rate
Saltmarsh bulrush	2/10 - 2/24 3/17 - 4/18	3 8	149 ± 37 26 ± 18
Cattails	2/7 - 2/24 3/17 - 4/18	4 8	179 ± 101 21 ± 19
Brass buttons	3/28 - 4/4	2	23 ± 13
Rabbitfoot grass	3/8 - 3/17 3/28 - 4/4	3 3	192 ± 153 37 ± 16
Inlet channel	3/7 - 3/8	1	205.9
Detritus	3/17 - 3/28	3	103 ± 108
Fungal mat-dry	2/24 - 3/3	2	108 ± 61
Fungal mat-wet	2/24 - 3/3	2	46 ± 13
Algal puddle	3/3 - 3/17	7	51 ± 18
Bare soil	4/7 - 4/18	6	24 ± 13

Table 3-2
Set I (2/7 - 4/18/95) Maximum (Max), Minimum (Min) and Pooled Mean Se Volatilization Rates (Mean ± Standard Deviation; μg Se m^{-2} d^{-1}) and Number of Measurements (n) From Various Vegetated and Non-Vegetated Sites in Pass 1 of the San Francisco Bay Wetland

		Volatilization Rate (μG Se m^{-2} d^{-1})		
Site Measured	**n**	**Mean ± SD**	**Max**	**Min**
Vegetated sites				
Saltmarsh bulrush	11	59 ± 61	175	2
Cattails	12	74 ± 96	311	4
Rabbitfoot	6	115 ± 129	332	26
Brass buttons	2	24 ± 13	33	14
Non-vegetated sites				
Inlet channel	1	206	206	206
Detritus	3	103 ± 108	223	13
Fungal mat (wet)	2	108 ± 61	151	65
Fungal mat (dry)	2	46 ± 13	55	36
Algal puddle	7	51 ± 18	77	23
Bare soil	6	24 ± 12	45	8

3.2 Set II Se Volatilization Measurements

The results of Set II volatilization measurements for vegetated sites are shown on Figure 3-2 and Table 3-3. Initial analysis of the data, indicated that weekly mean volatilization rates changed with time for saltmarsh bulrush and for saltgrass (ANOVA; $p<0.0001$ and $p<0.01$, respectively).

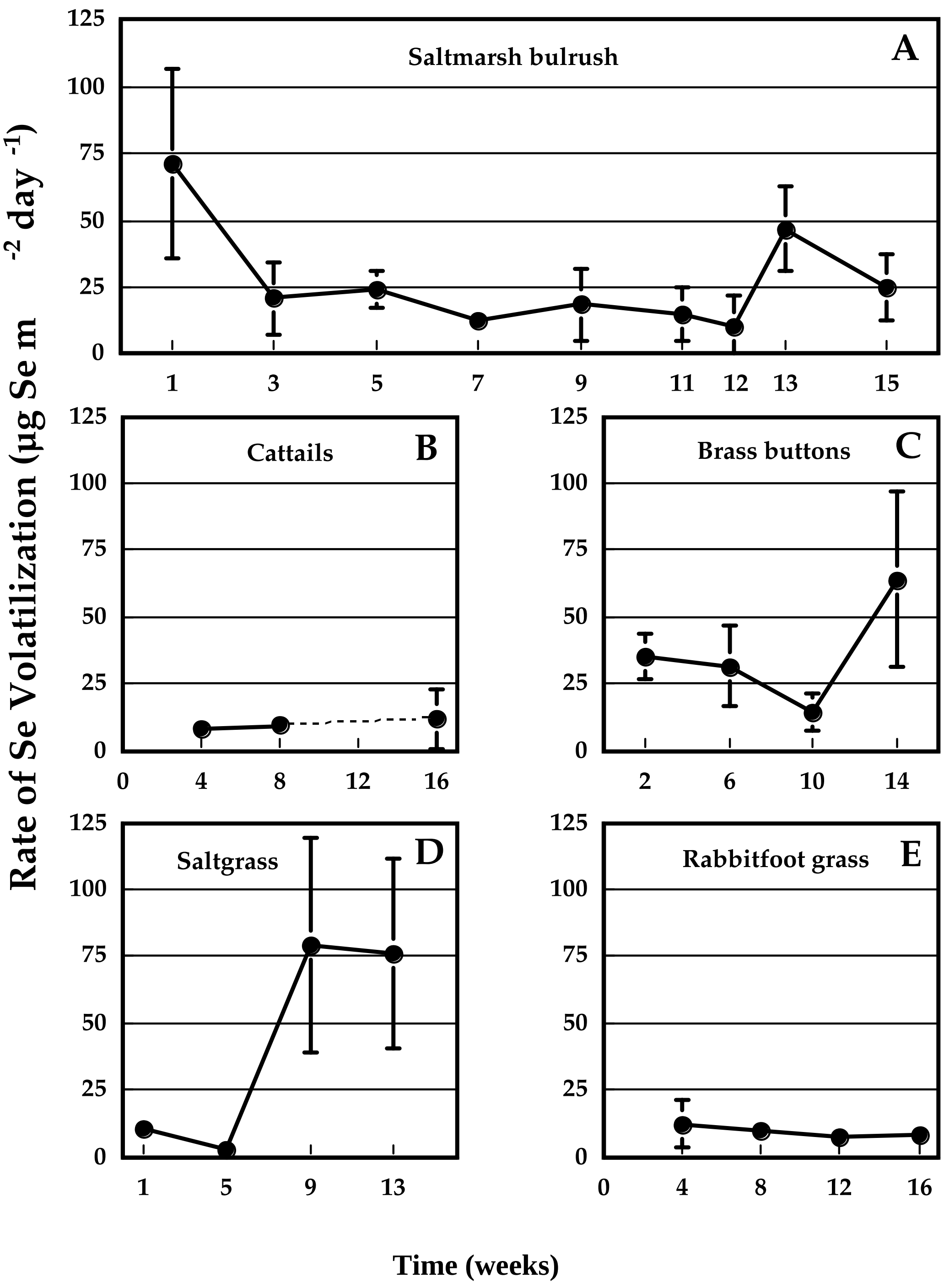

Figure 3-2
Se Volatilization Rates (Mean ± Standard Deviation; µg Se m^{-2} d^{-1}) Measured From Various Vegetated Sites in Pass 1 of the San Francisco Bay Wetland 6/23 - 10/15/95 (n=6 for Saltmarsh Bulrush Weeks 11 & 12; n=3 All Other Values)

A comparison of the weekly means for brass buttons (Figure 3-2(C)) indicated that the increase between weeks 10 and 14 was also significant (Tukey's test; $p<0.05$).

Table 3-3
Selenium Volatilization Rate (Mean ± Standard Deviation; µg Se m^{-2} d^{-1}) for Set II Measurements

Weeks of measurement are shown in parentheses beginning 6/23 and ending 10/13/95. Period 1 = 6/23 - 7/21; Period 2 = 7/21 - 8/18; Period 3 = 8/18 - 9/15; Period 4 = 9/15 - 10/13/95. (ND = no data; n= 6, 6, 12 and 15 measurements for Saltmarsh bulrush Periods 1, 2, 3 and 4, respectively; n=3 measurements for all other values, see Methods).

	Volatilization Rate (µg Se m^{-2} d^{-1})			
Site	**Period 1**	**Period 2**	**Period 3**	**Period 4**
Saltmarsh bulrush	46.1 ± 36.8 (1&3)	18.5 ± 7.6 (5&7)	15.7 ± 10.6 (9&11)	20.6 ± 18.8 (12,13&15)
Cattails	8.5 ± 4.7 (4)	10.1 ± 5.2 (8)	ND (12)	11.8 ± 11.2 (16)
Brass buttons	35.4 ± 8.7 (2)	31.7 ± 14.8 (6)	14.4 ± 6.7 (10)	64.1 ± 32.6 (14)
Saltgrass	10.5 ± 2.9 (1)	2.6 ± 0.7 (5)	79.2 ± 39.9 (9)	76.3 ± 35.5 (13)
Rabbitfoot grass	12.4 ± 8.9 (4)	9.6 ± 1.9 (8)	7.4 ± 3.5 (12)	8.3 ± 2.9 (16)
Inlet channel	166.9 ± 33.3 (2)	127.0 ± 28.4 (6)	69.7 ± 6.7 (10)	72.3 ± 11.4 (14)

Table 3-5 shows pooled mean values for Set II volatilization measurements along with maximum and minimum individual measurements. Maximum Se volatilization measurements ranged from 20 to 202 µg Se m^{-2} d^{-1} for rabbitfoot grass and the inlet channel, respectively. Although volatilization from the inlet channel gave the highest mean volatilization rate (109 ± 47 µg Se m^{-2} d^{-1}), Table 3-3 shows that weekly mean volatilization rates for saltmarsh bulrush, saltgrass and rabbitfoot grass sometimes exceeded inlet channel rates during the second two months of Set II measurements. This is important to note because Se concentrations were much higher in the inlet channel than in pore water at these vegetated sites (Table 3-4). These data suggest that vegetated systems might be more efficient in volatilizing Se than microbial systems (i.e. higher volatilization rate with lower Se concentration).

Table 3-4
Total Dissolved Selenium Concentration (Mean ± Standard Deviation; µg Se L^{-1}) in Sediment Pore Water at Volatilization Chamber Locations During Set II Measurements

Weeks of measurement, and number of measurements same as Figure 3-3.

Site	Selenium Concentration in Pore Water (µg Se L^{-1})			
	Period 1	Period 2	Period 3	Period 4
Saltmarsh bulrush	2.8 ± 0.7 (1&3)	4.2 ± 3.4 (5&7)	4.9 ± 3.4 (9&11)	6.2 ± 3.8 (12,13&15)
Cattails	3.5 ± 1.3 (4)	2.7 ± 0.3 (8)	ND (12)	9.3 ± 0 (16)
Brass buttons	6.0 ± 3.9 (2)	4.2 ± 1.9 (6)	2.66±0.59 (10)	7.7 ± 1.5 (14)
Saltgrass	5.3 ± 2.0 (1)	4.1 ± 1.2 (5)	12.8 ± 1.0 (9)	8.8 ± 2.3 (13)
Rabbitfoot grass	5.0 ± 2.0 (4)	6.7 ± 0.7 (8)	11.1 ± 4.0 (12)	16.1 ± 7.4 (16)
Inlet channel	17.1 ± 1.8 (2)	27.3 ± 3.8 (6)	33.0 ± 0.8 (10)	21.6 ± 2.1 (14)

Table 3-5
Set II (6/23 - 10/13/95) Maximum (Max), Minimum (Min), and Pooled Mean Se Volatilization Rates (Mean ± Standard Deviation; µg Se m^{-2} d^{-1}) From Various Vegetated and Non-Vegetated Sites in Pass 1 (n = Number of Measurements)

Site Measured	n	Volatilization Rate (µg Se m^{-2} d^{-1})		
		Mean ± SD	Max	Min
Vegetated sites				
Saltmarsh bulrush	39	23 ± 21	94	2
Cattails	9	10 ± 7	25	3
Brass buttons	12	36 ± 25	102	8
Rabbitfoot grass	12	9 ± 4	20	3
Saltgrass	12	42 ± 44	117	2
Non-vegetated sites				
Inlet channel	12	109 ± 47	202	62
Detopped bulrush	12	45 ± 39	123	7

Table 3-6 summarizes the significant relationships found between Se volatilization rate and the various parameters measured during Set II. The explicit regression relationships for each individual species are given in Appendix C. Table 3-6 shows that a relationship between volatilization rate and water Se found for each of the three plant species that showed changes in volatilization rate over time. Saltmarsh bulrush volatilization rate increased with SeIV concentration in surface-water samples (ANOVA; $p<0.03$), during weeks 11 and 12 when monitoring took place every other day. Brass buttons volatilization rates increased with Se IV concentration ($p<0.02$), and saltgrass volatilization rate increased with total Se concentration ($p<0.01$) in pore water samples. These results indicate that Se volatilization by vegetated sites is largely a function of available Se concentration. Se volatilization by the inlet channel (Figure 3-3(A) and Table 3-3); however, showed a different pattern; volatilization by the inlet channel decreased as Se and Se IV concentration increased ($p<0.05$ and $p<0.02$, respectively).

Table 3-6
Summary of Significant ($p<0.05$) Positive (+) and Negative (-) Relationships Between Se Volatilization Rate and Parameters Measured in Pass 1 of the San Francisco Bay Wetland (6/23 - 10/13/95)

[Se] = total dissolved selenium concentration in sediment pore water; [SeIV] = dissolved selenite concentration in sediment pore water; SeIV/Se = the proportion of selenite to total selenium in sediment pore water; EC = electrical conductivity; Eh = redox potential; shoot Se = total selenium concentration in shoot tissue; root Se = total selenium concentration in root tissue. The explicit relationships may be referenced in Appendix.

Site Measured	[Se]	[SeIV]	$\frac{\text{SeIV}}{\text{Se}}$	pH	EC	Eh	Shoot Se	Root Se
Inlet channel	-	-		-	+	+		
Saltmarsh bulrush							+	+
Cattails								
Brass buttons		+						
Saltgrass	+		+		+	+		
Rabbitfoot grass								
Saltmarsh bulrush × 2*		+	+	+	-			

***** relationships are with waters sampled at the sediment/surface water interface during the two-week intensive sampling period (9/1 - 9/15/95).

Analysis of the ‘outside’ temperature data logger (described above, used to monitor temperature differences inside and outside the volatilization chambers) indicated that mean daily temperature decreased from the beginning to the end of the experiment (Appendix C, $p<0.04$). Se volatilization has been shown to be influenced by factors such as: Se concentration (Karlson and Frankenburger, 1988), temperature (Frankenburger and Karlson, 1989) and water status (Zieve and Peterson, 1981; Frankenburger and Karlson, 1989 and Frankenburger and Karlson, 1994). Our results suggest the possibility that volatilization by the inlet channel (from algae and water-borne microorganisms) might be more temperature dependent, whereas volatilization in the wetland proper (from plants and soil microorganisms) might be more Se concentration dependent.

Overall, these results suggest that Se volatilization changes with time and Se concentration. Comparing Set I and Set II measurements indicate that Se volatilization rates for both cattails and bulrush were much greater earlier in the year. Furthermore, the systematic Set II measurements showed that volatilization rates change with time and Se concentration. Therefore, any future study directed at determining the overall significance of volatilization in terms of the yearly wetland Se mass balance should consider both seasonal and spatial variability. In addition, we found several instances where volatilization rates changed, with water chemistry parameters (e.g., pH), these results indicate possible future areas for research directed at optimizing environmental conditions for Se volatilization.

The results of the detopping experiments are shown in Figure 3-3(B) and Tables 3-7 and 3-8, which also show corresponding volatilization rates for unmanipulated saltmarsh bulrush sites during these same time periods. During weeks 3 and 7, volatilization rates were not different between the manipulated and unmanipulated sites. Volatilization rates; however, from detopped sites were significantly higher than control sites during weeks 11 and 15 (ANOVA; $p< 0.\ 0003$ and $p<0.05$, respectively). One reason that might explain why the first two detopping experiments had no significant effect is that the measurements for detopped bulrush during weeks 3 and 7 were made 3 and 4 days after detopping (respectively), whereas the measurements during weeks 11 and 15 began immediately after detopping. Earlier research in our lab indicated that volatilization increased for 72 hours after detopping and then decreased (Zayed and Terry, 1994). Overall, these results suggest that management strategies such as mowing might be used to enhance volatilization rates.

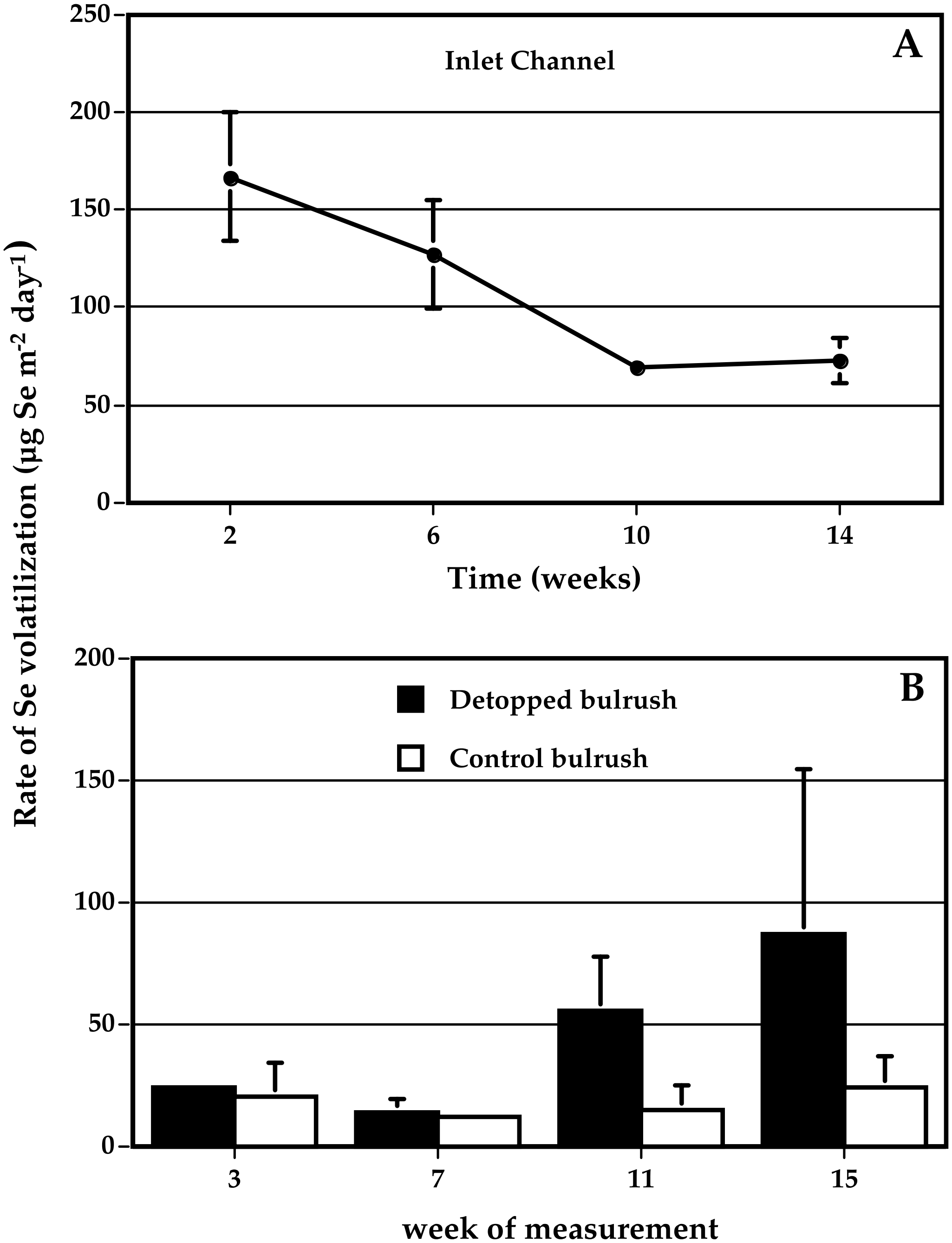

Figure 3-3
(A) Rates of Se Volatilization (Mean ± Standard Deviation; µg Se m^{-2} d^{-1}) Measured Over the Inlet Channel, and (B) Detopped and Intact Saltmarsh Bulrush Sites in Pass 1 of the San Francisco Bay Wetland 6/23 - 10/13/95

Table 3-7
Se Volatilization Rates (Mean ± Standard Deviation; µg Se m^{-2} d^{-1}) and Total Dissolved Se (Mean ± Standard Deviation; µg Se L^{-1}) in Sediment Pore Water for Detopped Saltmarsh Bulrush and Corresponding Values for Unmanipulated Saltmarsh Bulrush Sites in Pass 1 of the San Francisco Bay Wetland (6/23 - 10/13/95)

Volatilization rates are based on weekly means.

Week	n	Rate of Se Volatilization (µg Se m^{-2} d^{-1})		Pore Water Se Concentration (µg Se L^{-1})	
		Detopped Bulrush	Saltmarsh Bulrush	Detopped Bulrush	Saltmarsh Bulrush
3	3	24.13 ±1.72	20.78 ± 13.79	4.83 ± 1.51	2.88 ± 0.98
7	3	13.82 ± 5.85	14.22 ± 4.46	6.71 ± 2.62	3.83 ± 1.23
11	6	56.11 ± 22.36	14.81 ± 10.18	4.01 ± 0.84	3.02 ± 0.83
15	6	87.59 ± 67.0	24.72 ± 22.96	11.59 ± 1.44	9.93 ± 0

Table 3-8
Se Volatilization Rates (Mean ± Standard Deviation; µg Se m^{-2} d^{-1}) for Detopped Saltmarsh Bulrush and Corresponding Values for Unmanipulated Saltmarsh Bulrush Sites in Pass 1 of the San Francisco Bay Wetland 6/23 - 10/13/95 (n=3, Each Value)

Date of Measurement	Rate of Se Volatilization (µg Se m^{-2} d^{-1})	
	Detopped Bulrush	Saltmarsh Bulrush
7/10-7/14	24.1 ± 1.7	20.8 ± 13.8
8/7-8/11	13.8 ± 5.9	14.2 ± 4.5
9/1-9/6	45.1 ± 14.8	14.4 ± 10.4
9/6-9/8	67.2 ± 25.8	17.9 ± 14.1
9/29-10/2	125.4 ± 76.8	40 ± 25
10/2-10/6	49.8 ± 32.1	9.5 ± 0.5

3.3 Plant Tissue Se Measurements

Figure 3-4 and Table 3-9 show pooled plant root and shoot tissue Se concentrations. There were no significant differences between plant species in pooled plant tissue Se concentrations, which ranged from approximately 11 to 21 mg kg^{-1} dry weight (dw) in roots and 5 - 8 mg kg^{-1} dw in shoots. Plant tissue Se changed with time in only two instances: saltmarsh bulrush root Se decreased from 32 ± 14 to 14 ± 6.3 mg Se kg^{-1} dw ($p<0.005$) and rabbitfoot grass root increased from 16.3 ± 4.2 to 34.4 ± 7.3 mg Se kg^{-1} dw ($p<0.05$). The Se concentration in pore water; however, increased at all of the vegetated sites except brass buttons (Table 3-4 and Appendix). The explicit regression relationships found between plant tissue Se and the other parameters measured during Set II measurements are listed in Appendix.

Table 3-9
Pooled Values for Plant Shoot and Root Tissue Concentration (Mean ± Standard Deviation; mg Se kg^{-1} dw); Sediment Pore Water Se Concentration (µg Se L^{-1}) and Bioconcentration Factor (Tissue Se Concentration/Pore Water Se Concentration × 1000)

Samples were taken 6/23 - 10/13/95 (n=39, Saltmarsh bulrush ; n=9, Cattails; n=12, Brass buttons, Saltgrass and Rabbitfoot grass).

Species		Tissue Se (mg kg $^{-1}$ dw)	Pore-Water Se (µg Se L^{-1})	Concentration Factor
Saltmarsh bulrush	shoot	5.2 ± 3.2		1430
	root	15.5 ± 11.4	5.0 ± 3.2	4330
Cattails	shoot	6.1 ± 1.6		1580
	root	14.0 ± 7.8	5.2 ± 3.2	3560
Brass buttons	shoot	7.8 ± 3.2		1820
	root	15.1 ± 6.0	5.4 ± 2.8	3625
Saltgrass	shoot	7.1 ± 4.6		1070
	root	11.0 ± 3.3	7.7 ± 3.8	1770
Rabbitfoot grass	shoot	7.9 ± 6.2		850
	root	20.7 ± 11.4	9.8 ± 5.8	2520

Understanding how Se cycles through vegetation is important to control, or limit the bioavailability of Se in the wetland. Furthermore, since plant tissues concentrate large amounts of Se, vegetation removal can reduce soil Se loading overall by preventing plant-bound Se from accumulating in sediments. To address these issues, we calculated Se bioconcentration factors for shoots and roots for each species based on actual initial and final tissue and pore water Se concentration (Table 3-10) and based on pooled mean tissue and pore water Se concentrations (Table 3-9). Table 3-10 shows that initial and final concentration factors (ICF and FCF, respectively) varied substantially. For example, saltmarsh bulrush root ICF was 11,365 and root

FCF was 2,433. Similarly, cattails root ICF was 6,601 and root FCF was 1,622. These data show that plant tissue Se accumulation varies with factors such as Se concentration and time of year, or growing season. These results also suggest that there may be optimum times to remove vegetation to reduce overall Se loading to sediments.

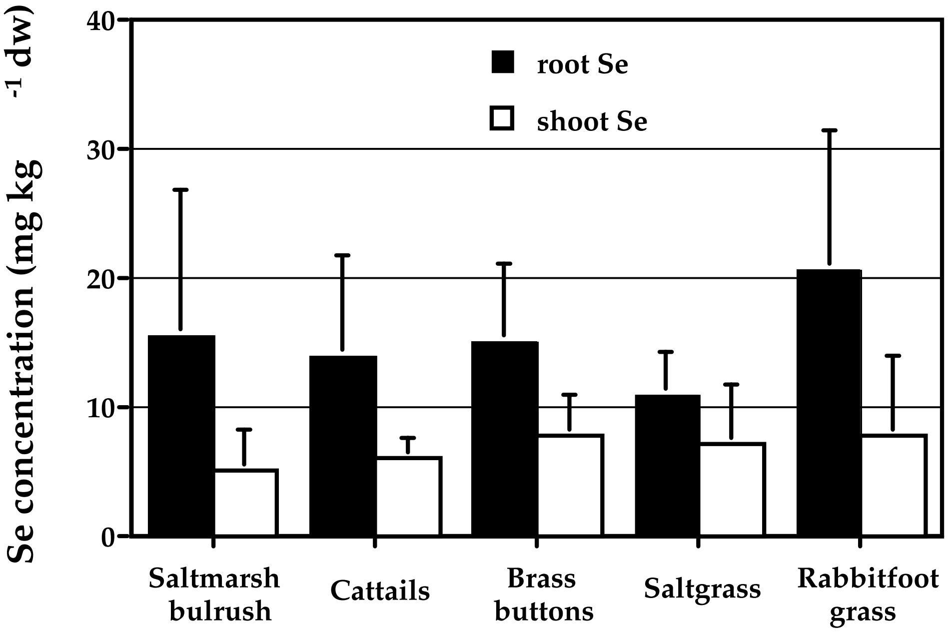

Figure 3-4
Plant Root and Shoot Tissue Se Concentrations (Mean ± SD; mg Se kg^{-1} dw) From Various Plant Species Sampled in Pass 1 of the San Francisco Bay Wetland

Values were pooled from samples taken monthly (bimonthly for Saltmarsh bulrush) 6/23 - 10/13/95 (n=39, Saltmarsh bulrush; n=9, Cattails; n=12, Brass buttons, Saltgrass and Rabbitfoot grass).

3.4 Sediment Se Measurements

The results of sediment Se analysis are shown on Table 3-11. There were no differences in Se concentration among or between species with, or without, respect to time. Pooled mean sediment Se concentrations at the various sites ranged from 2.1 ± 0.6 - 6.7 ± 5.1 mg Se kg^{-1} dw; individual measurements ranged from 0.5 - 16.0 mg Se kg^{-1} dw. Although no increase in sediment Se was observed, the data presented here are quite limited in that only samples from two sampling times (the first and last months of the study) were analyzed, and sediments were only sampled to a depth of 10 cm. More comprehensive sampling is needed to evaluate sediment overall Se loading and changes with time in the wetland.

Table 3-10
Pooled Mean, Initial (IV) and Final (FV) Values for Plant Root and Shoot Tissue Se, Initial and Final Values for Pore Water Se (± Standard Deviation) and Initial and Final Bioconcentration Factor Values (Tissue Se Concentration/Pore Water Se Concentration × 1000)

Samples were taken 6/23 - 10/13/95 (for tissue means: n=39, Saltmarsh bulrush; n=9, Cattails; n=12, Brass buttons, Saltgrass and Rabbitfoot grass; n=3 for initial and final values for tissue and water Se, see methods). Only Brass buttons pore water Se did not change significantly over time.

Species	Tissue	Tissue Se (mg kg^{-1} dw)			Pore-Water Se (µg L^{-1})		Concentration Factor	
		Mean	IV	FV	IV	FV	IV	FV
Saltmarsh bulrush	Shoot	5.2 ± 3.2	8.5 ± 2.9	7.4 ± 3.5	2.8 ± 0.7	6.9 ± 3.4	3,201 ± 600	1,362 ± 439
	Root	15.5 ± 11.4	30.6 ± 13.2	12.9 ± 6.7			11,365±2412	2,433 ± 923
Cattails	Shoot	6.1 ± 1.6	7.3 ± 1.3	6.3 ± 1.0	3.5 ± 1.3	9.3 ± 0	2,324 ± 635	674 ± 59
	Root	14.0 ± 7.8	20.3 ± 7.5	15.1 ± 6.5			6,601 ± 2437	1,622 ± 405
Brass buttons	Shoot	7.8 ± 3.2	6.4 ± 2.7	9.9 ± 3.8	6.0 ± 3.9	7.7 ± 1.5	1,166 ± 134	1,259 ± 184
	Root	15.1 ± 6.0	13.7 ± 10.9	15.2 ± 5.2			2,166 ± 199	2,033 ± 397
Saltgrass	Shoot	7.1 ± 4.6	3.6 ± 0.9	8.7 ± 8.0	5.3 ± 2.0	8.7 ± 2.3	712 ± 60	1,080 ± 536
	Root	11.0 ± 3.3	11.0 ± 3.3	12.1 ± 3.5			2,406 ± 713	1,447 ±297
Rabbitfoot grass	Shoot	7.9 ± 6.2	5.4 ± 1.7	14.9 ± 9.6	5.2 ± 2.0	16.1 ± 7.4	1,076 ± 72	880 ± 88
	Root	20.7 ± 10.7	16.3 ± 4.2	34.4 ± 7.3			3,552 ± 996	2,514 ± 767

Table 3-11
Mean, Maximum and Minimum Sediment Se Concentration (mg Se kg^{-1} dw) for Samples Taken at Volatilization Chamber Locations During 6/23 - 7/21 (Period 1) and 9/15-10/13/95 (Period 4) in Pass 1 of the San Francisco Bay Wetland (n=3, Periods 1 & 2; n=6, Mean Values)

	Selenium Concentration (mg Se kg^{-1} dw)				
Species	**Period 1**	**Period 4**	**Mean**	**Maximum**	**Minimum**
Saltmarsh bulrush	5.5 ± 4.0	3.8 ± 3.4	4.7 ± 3.5	10.1	1.5
Cattails	9.6 ± 5.2	2.3 ± 2.0	6.0 ± 5.3	14.0	0.5
Brass buttons	8.1 ± 7.2	5.3 ± 2.6	6.7 ± 5.1	16.0	2.1
Saltgrass	2.2 ± 0.6	2.4 ± 1.1	2.3 ± 0.8	3.2	1.2
Rabbitfoot grass	2.5 ± 0.5	1.8 ± 0.6	2.1 ± 0.6	3.1	1.2

3.5 Water Chemistry and Se Concentration Measurements

One of the main goals of this study was to investigate the significance of volatilization in terms of the wetland overall Se mass-balance (discussed below). To estimate rates of Se mass-removal, water flow rates (recorded twice daily) and Se concentrations (measured weekly) in and out of Pass 1, and out of Pass 3, were provided by Chevron (See Appendix). Chevron Se determinations estimate total Se, which includes particulate-bound Se, whereas UC Berkeley water Se determinations indicate total dissolved Se and dissolved Se IV (see Methods). Therefore, three different chemical forms of Se are reported here. The inlet and outlet parameters reported here were measured once per week (n = 1), whereas study site pore water values were pooled from replicate chamber measurements (n = 3 or 6). The regression relationships and mean values referred to in this section are complied in the Appendix for UC Berkeley data and for data supplied by Chevron.

The results of UC Berkeley water Se concentration measurements are shown on Figure 3-5(A) for Pass 1 Inlet and Outlet waters. The mean inlet total dissolved Se and dissolved Se IV concentrations were 23.0 ± 6.4 and 18.3 ± 6.9 µg Se L^{-1}, and the mean outlet (Pass 1) concentrations were 7.5 ± 4.0 and 4.6 ± 2.5 µg Se L^{-1}, respectively. Figure 3-6(A) shows Se concentration measurements made by Chevron for Pass 1 and Pass 3 outlet waters. The mean inlet and outlet (Pass 1) total Se concentrations were 25.8 ± 5 and 8.0 ± 3.2 µg Se L^{-1}, respectively.

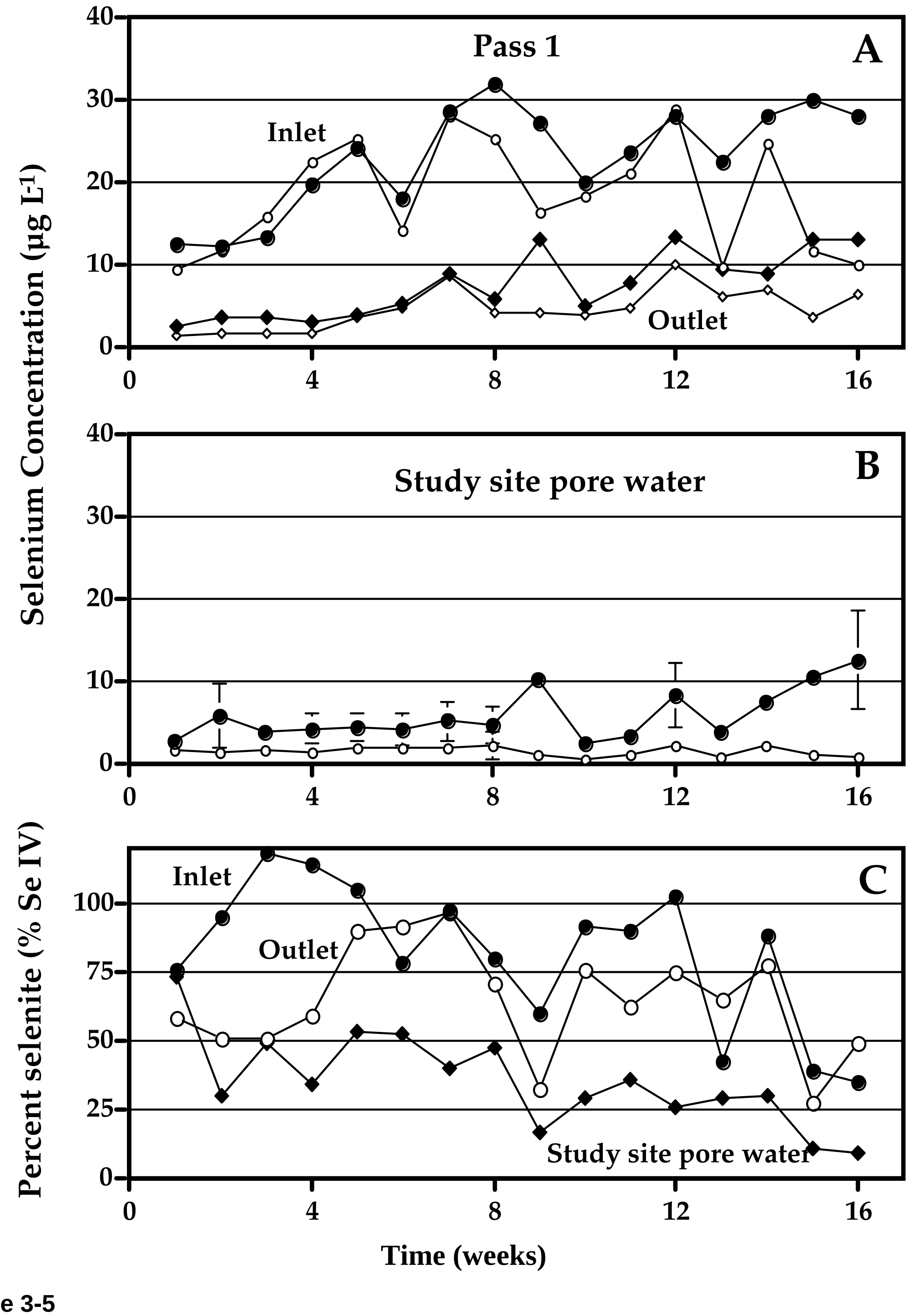

Figure 3-5
(A) Total Dissolved Selenium (Se) and Selenite (Se IV, Unshaded Symbols) Concentrations (µg Se L^{-1}) in Pass 1 Inlet and Outlet Waters; (B) Total Dissolved Se and Se IV (Unshaded Symbols) Concentrations (µg Se L^{-1}) in Sediment Pore Water at the Primary Study Site (Mean ± Standard Deviation, See Methods); (C) Percent Total Dissolved Se as Selenite (Se IV) in Pass 1 Inlet, Outlet and Study Site Pore Waters

All measurements made 6/23 - 10/13/95 in Pass 1 of the San Francisco Bay Wetland.

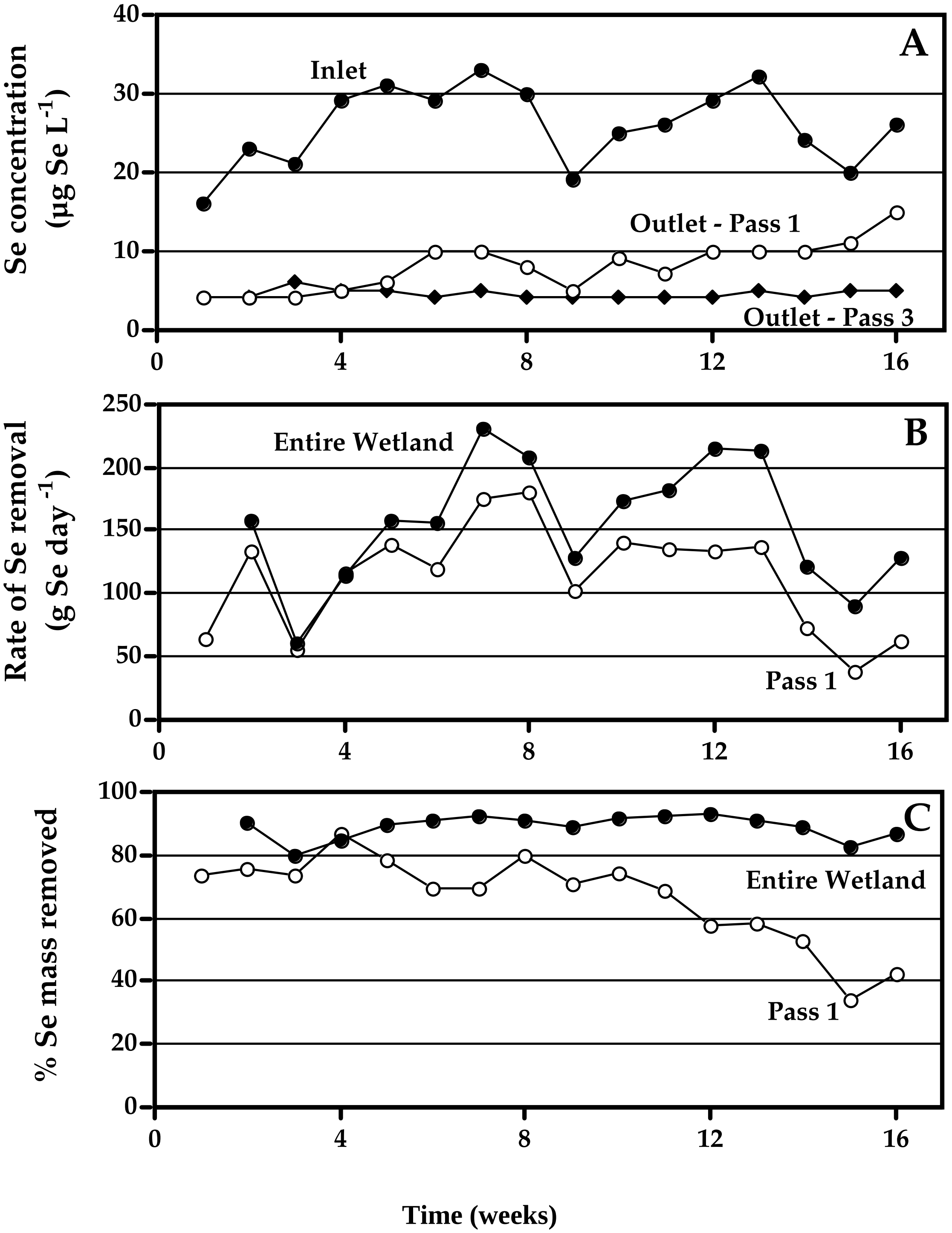

Figure 3-6
(A) Total Selenium (Se) Concentrations (µg Se L^{-1}) in Pass 1 and Pass 3 Outlet Waters of the San Francisco Bay Wetland; (B) Rate of Se Removal (g Se d^{-1}) for Pass 1 and the Entire Wetland; (C) Percentage of the Inlet Se Mass Removed by Pass 1 and the Entire Wetland

Data are for the period 6/23 - 10/13/95.

The mean Pass 3 outlet concentration was 4.5 ± 0.6 µg Se L^{-1}. Although, two different forms of total Se were measured (dissolved and dissolved + particulate) the two data sets for Pass 1 correspond remarkably well. The UC Berkeley Pass 1 inlet and outlet Se concentrations; however, showed small, but significant increases over time ($p<0.001$), whereas only Chevron Pass 1 outlet Se concentration increased over time. Chevron inlet Se concentration did not change over time. This difference indicates that the inlet waters contained a greater proportion of particulate-bound Se early in the study period.

Figure 3-5(B) shows total dissolved Se and dissolved Se IV concentrations in pore water at the primary study site. The pooled mean concentrations were 6.3 ± 3.9 and 1.6 ± 0.8 µg Se L^{-1} for total dissolved Se and Se IV, respectively. Pore water total dissolved Se concentrations were much less than inlet concentrations, and were generally lower than Pass 1 outlet concentrations.

Table 3-12
Mean Values for Water Chemistry Determinations in Pass 1 Inlet and Outlet Waters and Mean Water Flow Rates for Pass 1 and Pass 3 Outlet Waters in the San Francisco Bay Wetland (6/23 - 10/13/95)

Flow = Million Liters d^{-1}; EC = Electrical Conductivity (µS); Eh = Redox Potential (mV).

	Flow	pH	EC	Eh
Inlet	6.37 ± 1.4	7.34 ± 0.22	3556 ± 677	81 .5 ± 52.0
Outlet (Pass 1)	6.78 ± 3.01	7.31 ± 0.19	3954 ± 668	89.1 ± 42.4
Study site pore water	ND	7.21 ± 0.21	6869 ± 4394	75 ± 47
Outlet (pass 3)	3.85 ± 0.65	ND	ND	ND

Total Se in pore water increased over time ($p<0.0001$), as did inlet and outlet Se concentrations, but pore water Se IV concentration remained constant near 2.0 µg Se L^{-1}. Pore water total Se concentration was generally less than 5.0 µg Se L^{-1} for the first three months of the study, but then increased to near 10 µg Se L^{-1} at the end of the study period. Figure 3-5(C) shows that the percent Se IV in pore water decreased from approximately 50% to near 5% by the end of the study ($p<0.0001$). These data indicate that there was an increase in reduced forms of Se (Se^0 or Se^{-2}) in pore water, as oxidation (to Se VI) is unlikely to have occurred.

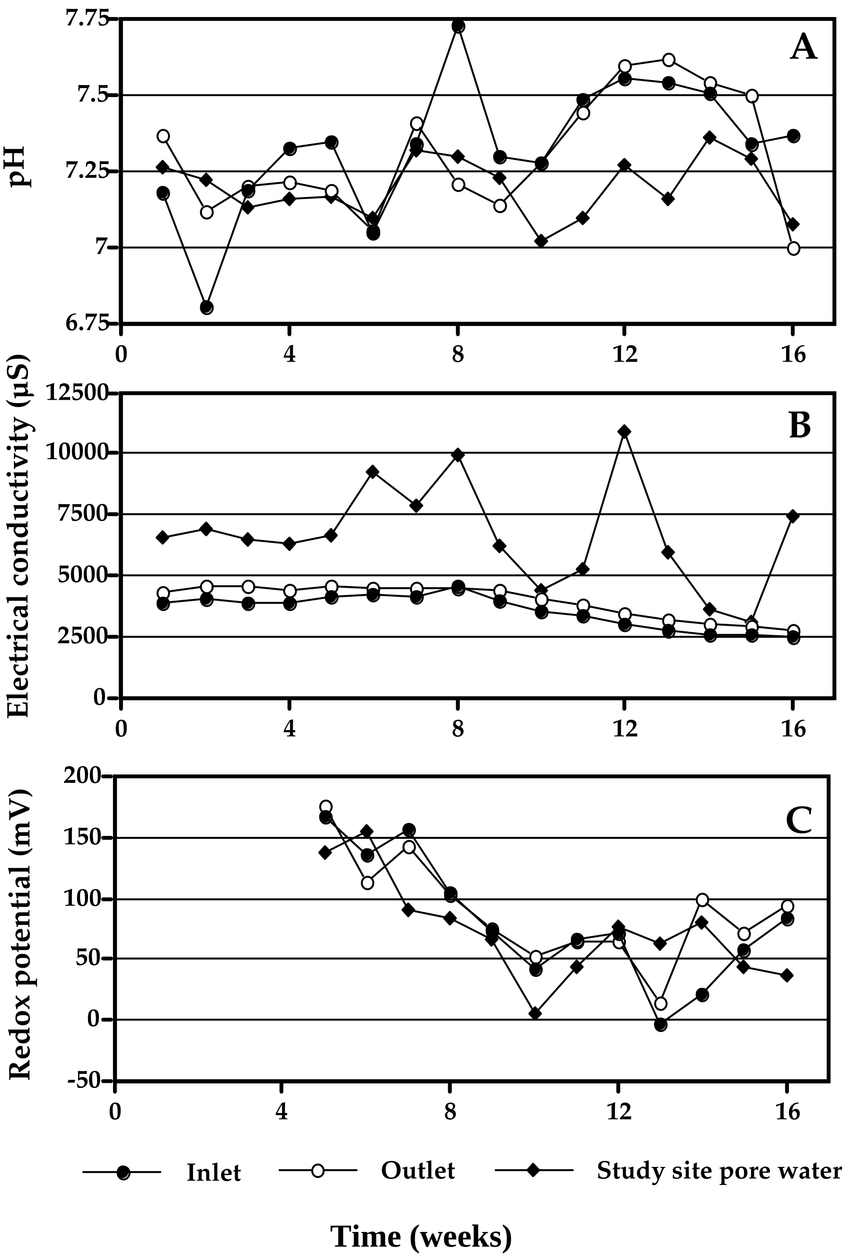

Figure 3-7
Results of Weekly (A) pH; (B) Electrical Conductivity (µS); and (C) Redox Potential (mV) Determinations for Pass 1 Inlet and Outlet Waters and for Sediment Pore Water at the Primary Study Site in Pass 1 of the San Francisco Bay Wetland (6/23 - 10/13/95)

Figure 3-7 shows the results of weekly water chemistry measurements. Figure 3-7(A) shows that inlet water pH increased to a small extent during the study period, from approximately 7.2 - 7.5 ($p<0.02$). Outlet water and sediment pore water pH did not change significantly with time; mean values were 7.31 ± 0.19 and 7.21 ± 0.21, respectively (Table 3-12). Figure 3-7(C) shows that the inlet, outlet and study site pore water Eh values were similar and each decreased with time ($p<0.0001$). Initial (week 5) actual values were 168, 175 and 138 mV for inlet, outlet and study site pore waters (pooled mean value for pore water), respectively; final actual values were 84, 94 and 38 mV, respectively. These data indicate that as time progressed during the study, the pH and redox potentials in the study site sediments became more favorable for the conversion of Se to reduced forms, such as selenides or elemental Se (Tokunaga et al, 1996; Jayaweera et al, 1996; Masschelyn et al, 1991). These data also suggest that the measured increase in total Se relative to Se IV in the study site pore water (see above; Figures 3-5(B) and (C) was due to an increase in elemental Se and/or organo-selenium compounds.

Figure 3-7(B) shows that the inlet and outlet EC values were similar and that each decreased with time from approximately 4000 - 2500 µS ($p<0.0001$). The mean outlet EC; however, was slightly higher than the inlet EC (Table 3-13; $p<0.0001$). The ECs of the study site pore waters were substantially higher than inlet and outlet waters and did not change over time; the mean value was 6869 ± 4394 (Table 3-12).

Tables 3-13 and 3-14 summarize the differences in the measured water chemistry parameters after passage through Pass 1 and the entire wetland. Total Se, total dissolved Se and dissolved Se IV concentrations were significantly reduced by 17.81 ± 1.2, 15.54 ± 1.10 and 13.73 ± 1.51 µg Se L^{-1}, respectively, after passage through Pass 1 ($p<0.0001$), and total Se was reduced by 21.93 ± 1.15 µg Se L^{-1} after passage through the entire wetland ($p<0.0001$). Inlet water pH and Eh were not significantly changed after passage through Pass 1, and EC was increased by 398 ± 39.67 µS ($p<0.0001$). This difference in EC; however, is likely to be an effect of increased concentration due to evapotranspiration of waters during passage through Pass 1.

The three forms of Se measured in the wetland inlet and outlet waters were compared by dividing the study period in to four 4-week periods (Figures 3-8(A) & (B)). Significant differences between concentrations of the three forms of Se were detected only during Period 1 in Pass 1 outlet waters, and Se IV concentration decreased below total Se and total dissolved Se concentrations in Period 4 (Tukey’s test; $p<0.05$). Overall, these data show that most of the Se in the inlet and outlet waters was in dissolved forms, especially Se IV. Figure 3-8(C) shows that pore water total dissolved Se concentration was greater than dissolved Se IV in each of the four periods, and that the percent Se IV decreased over time as compared to inlet and outlet waters (discussed above).

Table 3-13
Differences Between Mean Values and Standard Error (SE) for UC Berkeley Water Measurements in Pass 1 Inlet and Outlet Waters 6/23 - 10/13/95

[Se] = total dissolved Se (μg Se L^{-1}); Se (mass) = g Se d^{-1}; EC = electrical conductivity (μS); Eh = redox potential (mV).

Relationship	Mean Difference ± SE	Significance
Inlet [Se] – Outlet [Se]	15.54 ± 1.10	p<0.0001
Inlet [SeIV] - Outlet [SeIV]	13.73 ± 1.54	p<0.0001
Inlet Se - Outlet Se (mass)	96.64 ± 10.45	p<0.0001
Inlet Se IV - Outlet Se IV (mass)	86.54 ± 11.75	p<0.0001
Inlet pH - Outlet pH	0.03 ± 0.05	NS
Inlet EC - Outlet EC	-398.0 ± 39.67	p<0.0001
Inlet Eh - Outlet Eh	-7.61 ± 7.1	NS

Table 3-14
Differences Between Mean Values and Standard Error (SE) for Chevron Water Se Measurements in Pass 1 and Pass 3 Outlet Waters 6/23 - 10/13/95

[Se] = total dissolved Se (μg Se L^{-1}); Se (mass) = g Se d^{-1}.

Relationship	Mean Difference ± SE	Significance
Inlet [Se] – Outlet [Se] (Pass 1)	17.81 ± 1.20	p<0.0001
Inlet [Se] - Outlet [Se] (Entire wetland)	21.93 ± 1.15	p<0.0001
Inlet Se - Outlet Se (mass) (Pass 1)	112.42 ± 10.69	p<0.0001
Inlet Se - Outlet Se (mass) (Entire wetland)	155.62 ± 12.78	p<0.0001

3.6 Mass-Flux and Removal Calculations

Mass-fluxes for UC Berkeley water Se measurements in and out of Pass 1 are shown on Figures 3-9(A) & (B), the corresponding mean values and statistical relationships may be referenced in Appendix A. Discussion of Se mass-flux and removal in this section; however, is limited to the Chevron data set (Figure 3-6) because these reflect true mass-fluxes (dissolved + particulate forms).

Figure 3-6(B) shows the calculated daily rates of total Se removal over time for Pass 1 and for the entire wetland. The weekly values for Se removal varied substantially with time. In addition, rates for Pass 1 and the entire wetland increased and decreased concomitantly. The lowest rate of Se removal for the entire wetland and for Pass 1 was approximately 55 g Se d^{-1} during the third week of the study. Mass removal then increased through week 12 to over 140 and 200 g Se d^{-1} for Pass 1 and the entire wetland, respectively. During the last few weeks of the study, removal then decreased to approximately 50 g Se d^{-1} for Pass 1 and 100 g Se d^{-1} for the entire wetland. The pooled mean removal rates were 112.4 ± 42.8 and 155.6 ± 49.5 g total Se d^{-1} for Pass 1 and the entire wetland, respectively.

To evaluate Se mass-removal efficiency, rates of Se removal as a function of the inlet mass were calculated for Pass 1 and for the entire wetland using the equation [(1- (outlet mass/inlet mass)) × 100]. Figure 3-6(C) shows that the percent of Se removed by the entire wetland was relatively constant during the study period: 89.4 ± 0.6% (mean ± SE). The percent of Se removed by Pass 1; however, decreased from nearly 80% at the beginning, to near 40% by the end of the study period ($p<0.0001$). These data were further evaluated by dividing the data into 2 periods (weeks 1-8 and weeks 9-16; Table 3-15). There was no difference in the percent Se removal by the entire wetland between the two periods. The percent Se removed by Pass 1; however, significantly decreased between the two periods from 75.8 ± 2.2% - 57.6 ± 4.4% ($p<0.004$). This 25% decrease in the ability of Pass 1 to remove Se is important to note because it shows that Se removal by wetlands can vary with time, and that wetland management practices should consider this variability in order to optimize Se removal.

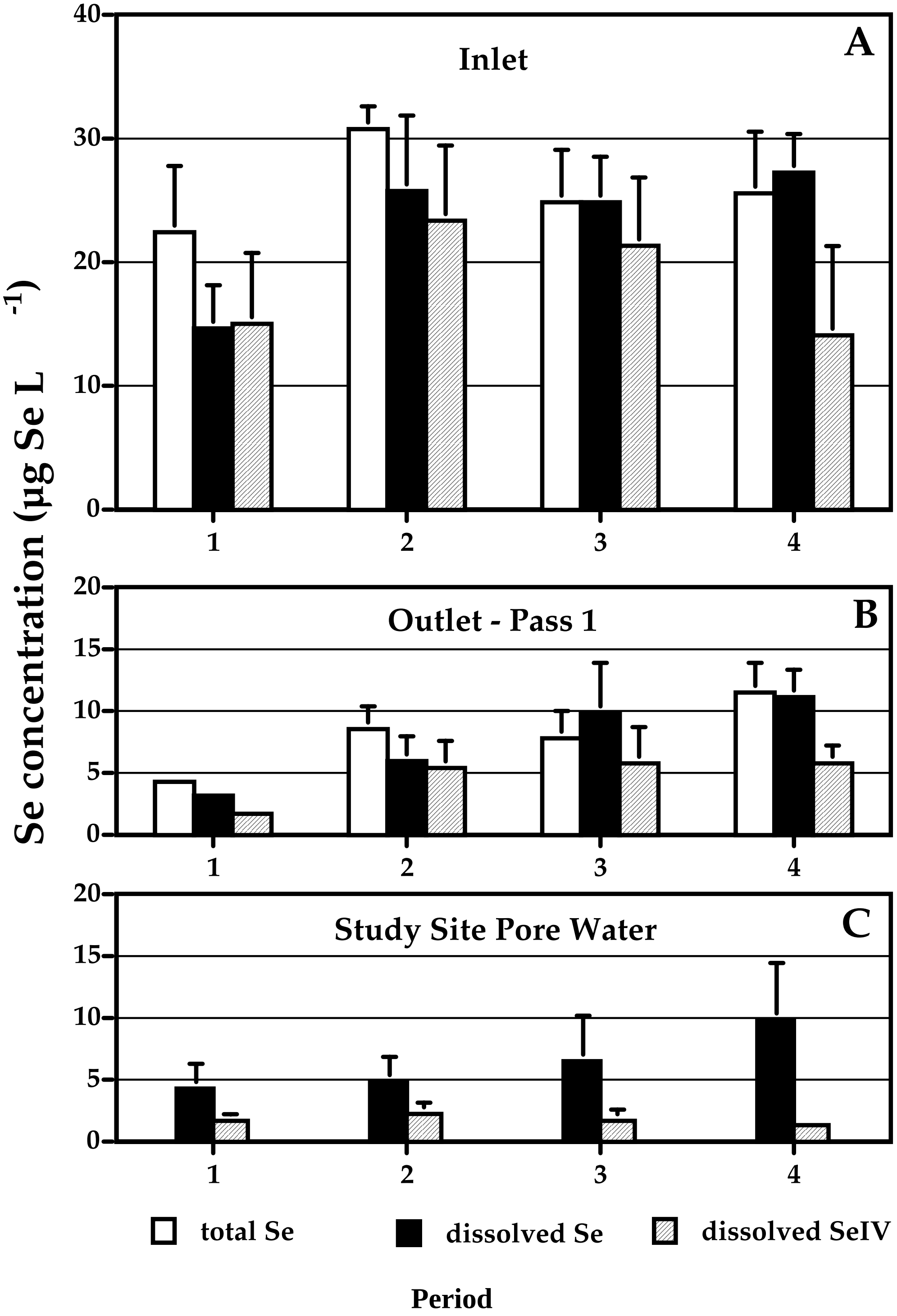

Figure 3-8
Comparison of Weekly Measurements for Total Se, Total Dissolved Se and Dissolved Se IV Concentrations (µg Se L^{-1}) in (A) Pass 1 Inlet, and (B) Pass 1 Outlet Waters and (C) Comparison of Weekly Measurements for Total Dissolved Se and Se IV in Sediment Pore Water at the Primary Study Site in Pass 1 of the San Francisco Bay Wetland (6/23 - 10/13/95)

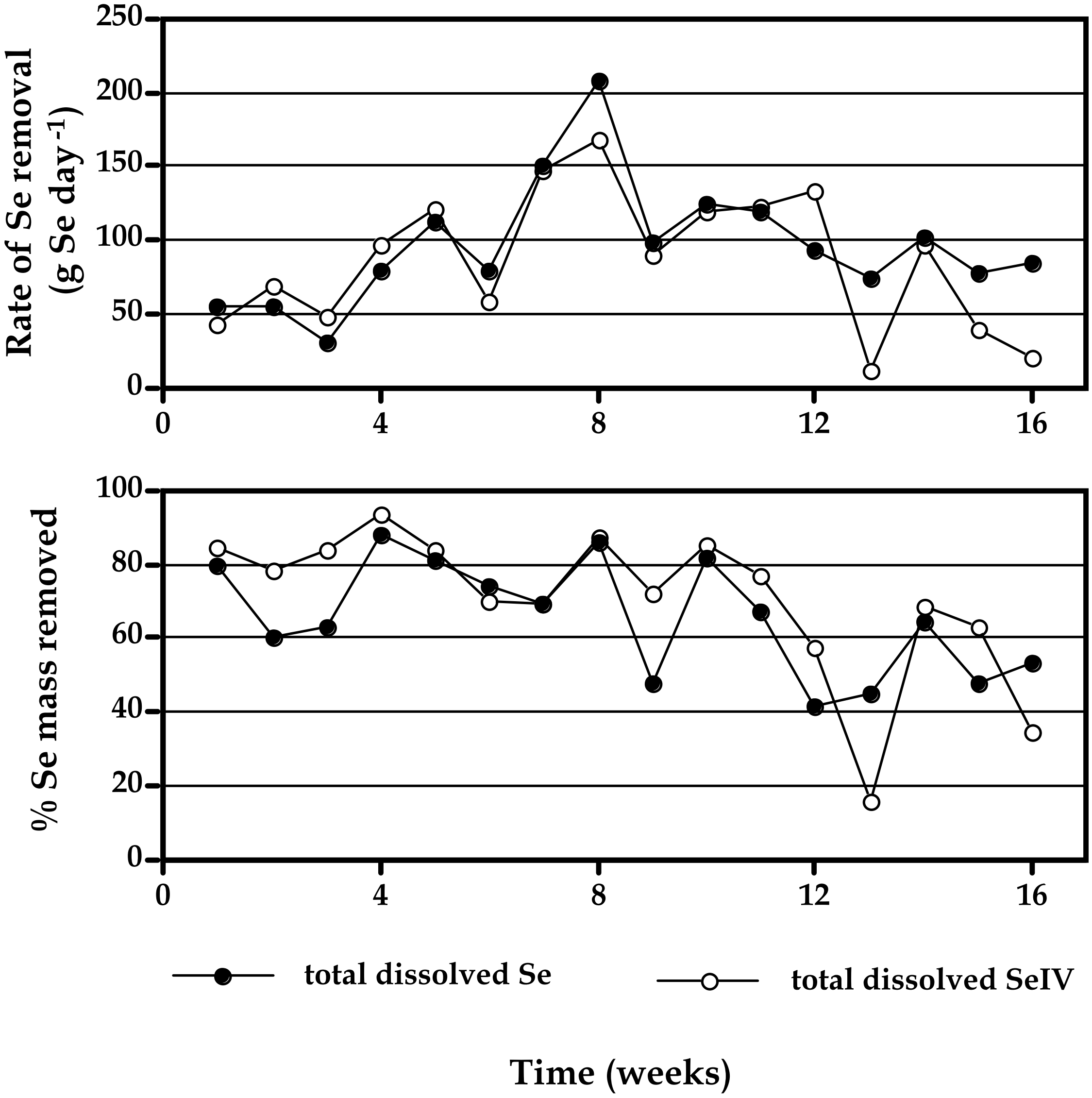

Figure 3-9
(A) Rates of Total Dissolved Se and Dissolved Se IV Removal (g Se d-1); and (B) Percentage of Inlet Se Mass Removed by Pass 1 of the San Francisco Bay Wetland (6/23 - 10/13/95)

Table 3-15
Mean % Se Mass Removal and Associated Error for the Entire San Francisco Bay Wetland and for Pass 1 During the 16-Week Period 6/23-10/13/95

Calculations are based on the Chevron data set for total Se (dissolved + particulate forms).

	Period		
	Week 1-8	**Weeks 9-16**	**Weeks 1-16**
Pass 1	75.8 ± 2.2%	57.6 ± 4.4%	67.1 ± 2.8%
Entire wetland	88.4 ± 0.8%	90.1 ± 0.7%	89.4 ± 0.6%

Organic matter, nutrient and plant-cycling are highly seasonal processes in temperate wetlands. Water chemistry measurements began the first day of summer (6/23) and ended well into autumn (10/13). Furthermore, saltmarsh bulrush and cattails began setting seed early in July and by the end of the study period these two plant species had nearly completely senesced. Thus, the observed decrease in the ability of Pass 1 to remove Se over the study might be explained by seasonal factors such as a decrease in plant productivity, or plant-related microbial processes. Allen (1991) suggested that the ability of outdoor experimental stream-wetland systems to remove Se from water was seasonally dependent. She found an increase in Se removal beginning in May, peaking in late summer, and then declining through October and suggested that the greatest amount of plant biomass was present during the time of maximum Se removal. Horne (1994) also observed a similar seasonal pattern, with a winter-spring peak and summer depression, in his study of Se cycling in biota at Kesterson. He noted; however, that *Scirpus* root Se did not peak until early summer.

To summarize, these results show that the San Francisco Bay wetland consistently removed approximately 90% of the mass of Se entering it during the 16-week period, and that 65-85% of this reduction occurred in Pass 1 (Table 3-15 and Figure 3-6(C)). The mass removal rates for the entire wetland ranged between 55 and 200 g Se day^{-1}. Furthermore, the data show that although the efficiency of Pass 1 in removing Se decreased by 25% during the study period, Se removal by the entire wetland remained constant. Overall, these data indicate that the wetland operating parameters (e.g., loading rates and residency times) during this study were within the optimum range to buffer any decrease in the ability of the wetland to remove Se due to seasonal, or other, factors.

To determine if volatilization could represent a significant pathway for Se removal by the wetland, we calculated the percent of Se removed due to volatilization using the mean and 95% confidence limits of the mass removal data for the entire wetland (156 and 183 - 128 g Se d^{-1}, respectively), and a hypothetical range of volatilization rates (0 - 350 µg Se m^{-2} d^{-1}; Figure 3-10) using the following equation: $P = (VA/W) \times 100$, where P is the percent removed due to volatilization, V is the volatilization rate (µg Se m^{-2} d^{-1}), A is the total area of the wetland (3.64×105 m^{-2}), and W is the wetland Se removal rate (µg Se d^{-1}). As discussed above, we have shown that Se volatilization processes in the wetland are dynamic and vary with factors such a time (or season) and available Se concentration, and our actual volatilization measurements were made only in a limited area of Pass 1. Therefore, actual values for V for the entire wetland are unknown. This comparison is also limited because a proportion of the actual mass removed (particulate-bound Se) is likely to be considerably less available to be volatilized. Using Figure 3-10; however, one may calculate P for various values of V. For example, the highest rate of volatilization measured in the wetland was 330 µg Se m^{-2} d^{-1} (Table 3-2). Figure 3-10 shows that if this were the mean volatilization rate across the entire wetland, the corresponding percent removal due to volatilization would be approximately 77%. The lowest volatilization rates measured were around 10 µg Se m^{-2} d^{-1}, this rate would give a P value of 2.34%. Saltmarsh bulrush was the most dominant plant in the wetland. Saltmarsh bulrush mean volatilization rates in February, June and October, were 150, 70 and 25 µg Se m^{-2} d^{-1} (Tables 3-1 & 3-16 and Figure 3-2); these rates correspond to percent removals of 35%, 17% and 6%, respectively.

Thus, the present study has shown that both high and low rates of Se volatilization occur in the San Francisco Bay wetland. We have also shown that it will be possible to accurately determine the proportion of Se removed through volatilization with a more comprehensive study designed to consider temporal and spatial factors. Although, interpretation of these data is limited, we believe that volatilization could account for as much as 10 - 30% of the Se removed by the wetland. This proportion is consistent with findings of Cooke and Bruland (1987), who calculated that as much as 30% of the Se entering the Kesterson Reservoir was volatilized.

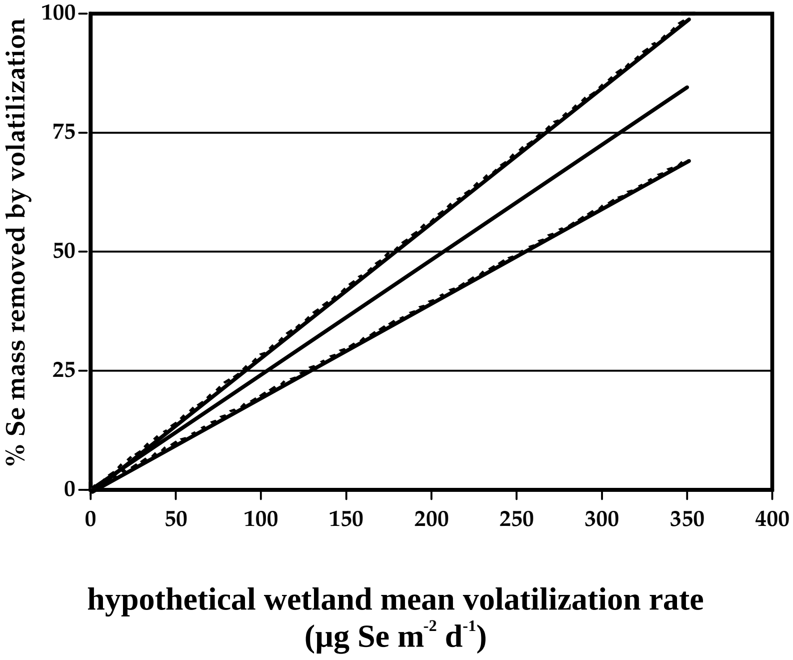

Figure 3-10
Percent of Se Mass Removed From Water by the Entire Wetland Due to a Hypothetical Range of Volatilization Rates (µg Se m^{-2} d^{-1}) Which Represent (Unknown) Mean Volatilization Rates for the Entire Wetland

Solid line represents the mean mass of total Se removed by the entire wetland (156 g Se d^{-1}); hatched lines represent the 95% upper and lower limits of the mass removal data (183 - 128 g Se d^{-1}, respectively).

Table 3-16
Maximum Mean Rates of Se Volatilization (± Standard Deviation; µg Se m^{-2} d^{-1}), Number of Measurements (n) and Dates of Measurement From Various Vegetated and Non-Vegetated Sites in Pass 1 of the San Francisco Bay Wetland

Data are from Set I and Set II measurements (2/7 - 4/18 and 6/23 - 10/13/95, respectively).

Site	Volatilization Rate (µg Se m^{-2} d^{-1})	n	Dates Measured
Vegetated sites:			
• rabbitfoot grass	190 ± 150	3	3/8 - 3/17
• cattail	180 ± 100	4	2/7- 2/24
• saltmarsh bulrush	150 ± 40	3	2/10 - 2/24
• saltgrass	80 ± 40	3	8/18 - 8/25
• brass buttons	60 ± 30	3	9/22 - 9/29
Non-vegetated sites:			
• inlet channel	170 ± 30	3	6/30 - 7/7
• fungal mat	110 ± 60	2	2/24 - 3/3
• detritus on water	100 ± 110	3	3/17 - 2/28
• algal puddle	50 ± 20	7	3/3 - 3/17
• unvegetated sediment	20 ± 10	6	4/7 - 4/18

3.7 Conclusion

The first phase of the project was successful on many levels. The results presented in this report show that 1) the San Francisco Bay wetland is highly effective in removing Se from refinery wastewater; 2) high rates of Se volatilization are present in the San Francisco Bay wetland, over vegetated and non-vegetated sites; and 3) there is potential to increase the extent of Se removal through volatilization by wetland management practices such manipulation of water levels, water chemistry, temperature or plant and microbial factors.

3.8 Acknowledgments

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A

PLANT DIGEST PROTOCOL

Things You Will Need:

Large digestion tubes (one per sample), digestion tube rack, large funnels (one per tube), concentrated nitric acid, 15 mL disposable centrifuge tubes (one per sample), rack for centrifuge tubes, test tubes with scratch at 10 mL volume, rack for scratchy tubes, caps for scratchy tubes, DI water squirt bottle, Kim Wypes, sharpie, clear tape (usual set-up).

Day One:

Get “things you will need” together, and label test tubes. Weigh 100.0 mg of sample and place into labeled digest tube. Add 1.0 mL of conc HNO_3 to each sample. Put one funnel on top of each tube. Let tubes sit in rack - in hood - over night at room temperature.

Day Two:

Place tubes into digest block rack, and put samples into digest block. Heat at 130°C for about 5 hours. Samples should be clear. When done, transfer tubes to wood rack, and let cool. Carefully pour samples into appropriately labeled centrifuge tube. Rinse each digest tubes two times with DI water, keeping overall volume to < 10.0 mL. Dilute each sample to 10.0 mL with DI water.

Day Three:

Pipette 1.0 mL of sample into appropriately labeled scratchy tube. Add 1.0 mL of H_2O_2 to each sample. Heat at 95°C for 30 minutes. Cool. Add 5.0 mL HCl , heat at 95°C for 20 minutes. Dilute to 10 mL with DI water, if necessary. Analyze.

B

CHARCOAL FILTER EXTRACTION AND PREPARATION FOR ANALYSIS

Materials Needed - Extraction

- one charcoal trap
- one 500 mL Nalgene bottle (per trap)
- 0.05 M NaOH stock solution
- H_20_2
- 250 mL graduated cylinder
- pestle (from big mortar and pestle)
- **general:** Sharpie, KimWypes, paper towels, DI water etc.

Carefully weigh, and record weight of entire trap. Cut 1/4 sub-sample from trap and carefully record weight of sub-sample). Cut 1/4 sub-sample into small pieces and put into labeled Nalgene Bottle. Measure 200.0 ml of extraction solution (160 mL 0.05 M NaOH + 40.0 mL H_2O_2) into each Nalgene bottle. Use pestle to make sure entire sample is immersed. Leave cap slightly loose for 24 hrs to prevent pressure build-up.

Materials Needed - Analysis Preparation

- one sample (one Nalgene bottle)
- test tubes - **per each sample: one** large (135 mm) test tube (to filter into) and **two** test tubes with 10.0 ml calibration scratch, **caps** for scratchy tubes
- H_2O_2
- funnels, filter paper (#1 Whatman 7.0 cm dia.)
- concentrated HCl
- **general:** clear tape, Sharpie, test tube racks, small beaker for H_2O_2, 1000 µL pipette, pipette tips etc.

Heat water bath to 91°C. Shake samples. Filter one funnel-full of sample (about 5.0 mls) into (“to filter into”) test tubes. Pipette 500 µL of filtered sample into 10.0 mL scratchy tubes (**two** tubes per sample). Add 500 µL H_2O_2 to each sample. Boil off H_2O_2 at 91°C (about 30 minutes). Cool and add 5.0 ml HCl. Cap and heat at 91°C for 20 minutes. Cool, and dilute to 10.0 mL final volume with DI water. Analyze.

C

WATER ANALYSIS PROCEDURE

All water samples were taken using Rhizon soil water samplers (0.1 µm pore size) with 10.0 mL Vacutainers.

Soil pore-water samples are a top 10 cm composite.

Inlet and Outlet waters were sampled 10.0 cm below the surface.

Water pH, EC and Eh were measured in the field, immediately after sampling.

Samples were then stored @ -80°C until analysis.

Selenite was analyzed by introducing the sample directly into the hydride generator.

Samples are prepared for total dissolved Se analysis by mixing 2.25 mL of sample with 0.5 ml of a 2.0% ammonium persulfate solution and 2.25 mL of concentrated hydrochloric acid. The mixture was then heated at 95°C for 15 -30 minutes. Sample volume was then adjusted, if necessary, with distilled water.

D

TOTAL ACID DIGEST FOR SEDIMENTS

Sediment Preparation

Air-dry samples.

Remove organic material.

Crush with mortar and pestle. Sift through sieve.

Place 1.0 gram of soil into Teflon FEP tube.

Add 5.0 ml concentrated nitric acid, 1.0 mL 30% hydrogen peroxide. Heat at 90°C until samples are damp. Add 15 mL of 6M HCl. Sonicate for 3 minutes and return to heating block for 24 hours. Centrifuge samples for 3 - 5 minutes at 7000 rpm. Decant supernatant into 50 mL volumetric flask. Add 10.0 mL HCl to each tube, sonicate for 3 minutes. Return to heating block for 30 minutes. Centrifuge again, and decant supernatant into volumetric flasks. When warm, add 0.5 mL of 8.0 M urea. Top-off with distilled water. Analyze.

E

LINEAR REGRESSION AND STATISTICAL ANALYSES

Significant linear regression relationships ($p<0.05$) for **inlet channel** measurements 6/23 - 10/15/95. vol rate = selenium volatilization rate (µg Se m^{-2} day^{-1}); temp = temperature (°C); [Se] = total dissolved selenium concentration (µg Se L^{-1}) inside volatilization chambers; [SeIV] = dissolved selenite concentration (µg SeIV L^{-1}) inside volatilization chambers; EC = electrical conductivity (µS); Eh = redox potential (mV).

Relationship	**Regression Equation**	r^2	**Significance**
• volatilization decreased when [Se] increased	vol rate = 210.23 - 4.09 [Se]	0.332	p<0.05
• volatilization decreased when [SeIV] increased	vol rate = 247.35 - 6.02 [SeIV]	0.428	p<0.02
• volatilization decreased over time	vol rate = 177.18 - 8.53 week	0.730	p<0.0004
• temperature decreased over time	temp = 19.68 - 0.11 week	0.067	p<0.03
• volatilization decreased as pH increased	vol rate = 1758.04 - 224.73 pH	0.725	p<0.0004
• volatilization increased as EC increased	vol rate = -58.82 + 0.047 EC	0.482	p<0.02
• volatilization increased as Eh increased	vol rate = 1.28 + 1.21 Eh	0.538	p<0.04

Significant linear regression relationships ($p<0.05$) for **saltmarsh bulrush** measurements 6/23 - 10/15/95. vol rate = selenium volatilization rate (µg Se m^{-2} day^{-1}); [root Se] = total selenium concentration (mg Se kg^{-1} dw) in root tissue; [shoot Se] = total selenium concentration (mg Se kg^{-1} dw) in shoot tissue; [Se] = total dissolved selenium concentration (µg Se L^{-1}) in sediment pore water; [SeIV] = dissolved selenite concentration (µg SeIV L^{-1}) in sediment pore water.

Relationship	**Regression Equation**	**r^2**	**Significance**
• volatilization increased with [shoot Se]	vol rate = 6.24 + 3.48 [shoot Se]	.202	$p<0.02$
• volatilization increased with [root Se]	vol rate = 13.84 + 0.73 [root Se]	0.148	$p<0.05$
• [root Se] increased with [shoot Se]	[root Se] = 1.01 + 2.87 [shoot Se]	0.493	$p<0.0001$
• [root Se] increased with pore-water [SeIV]	[root Se] = 2.56 + 11.23 [SeIV]	0.258	$p<0.01$
• pore-water [Se] increased over time	[Se] = 2.49 + 0.32 week	0.252	$p<0.008$
• pore-water [SeIV/Se] decreased over time	[SeIV/Se] = 0.68 - 0.04 week	0.657	$p<0.0001$
• [shoot Se] did not change over time			
• [root Se] decreased over time	[root Se] = 32.53 - 1.69 week	0.398	$p<0.0004$

Significant linear regression relationships ($p<0.05$) for **saltmarsh bulrush** measurements **made every two days** 9/1 - 9/15/95. vol rate = selenium volatilization rate (µg Se m^{-2} day^{-1}); [shoot Se] = total selenium concentration (mg Se kg^{-1} dw) in shoot tissue; [root Se] = total selenium concentration (mg Se kg^{-1} dw) in root tissue; [Se] = total dissolved selenium concentration (µg Se L^{-1}) in water samples at the sediment/surface water interface; [SeIV] = dissolved selenite concentration (µg SeIV L^{-1}) in surface water; EC = electrical conductivity (µS).

Relationship	**Regression Equation**	**r^2**	**Significance**
• volatilization increased when surface water [SeIV] increased	vol rate = 7.29 + 2.46 [SeIV]	0.249	p<0.04
• volatilization increased when surface water [SeIV/Se] increased	vol rate = 2.41 + 29.47 [SeIV/Se]	0.327	p<0.02
• volatilization increased when surface water pH increased	vol rate = -240.53 + 35.18 pH	0.343	p<0.01
• volatilization decreased as surface water EC increased	vol rate = 37.4 - 0.0052 EC	0.408	p<0.004
• shoot [Se] did not change over time			
• root [Se] did not change over time			

Significant differences ($p<0.05$) between sediment pore water samples and samples taken at the sediment/surface water interface for **saltmarsh bulrush**. Measurements were made every two days for two weeks in the primary study site of Pass 1 9/1 - 9/15/95. vol rate = selenium volatilization rate (µg Se m^{-2} day^{-1}); [Se] = total dissolved selenium concentration (µg Se L^{-1}); [SeIV] = dissolved selenite concentration (µg Se IV L^{-1}); EC = electrical conductivity (µS); Eh = redox potential (mV).

Relationship	**Mean Difference**		**Significance**
• surface [Se] was not different from pore water [Se]			
• surface [SeIV] was not different from pore water [SeIV]			
• surface [SeIV/Se] was not different from pore water [SeIV/Se]			
• surface pH was different from pore water pH	-0.1129		p<0.04
• surface EC was different from pore water EC	1864.76		p<0.0004
• surface Eh was not different from pore-water Eh			

Significant linear regression relationships ($p<0.05$) for **cattails** measurements 6/23 - 10/15/95. [Se] = total dissolved selenium concentration (µg Se L^{-1}) in sediment pore water; [SeIV] = dissolved selenite concentration (µg Se L^{-1}) in sediment pore water; [shoot Se] = total selenium concentration (mg Se kg^{-1} dw) in shoot tissue; [root Se] = total selenium concentration (mg Se kg^{-1} dw) in root tissue.

Relationship	**Regression Equation**	**r^2**	**Significance**
• pore-water [Se] increased over time	[Se] = 0.224 + 0.53 week	0.789	p<0.002
• pore-water [SeIV/Se] decreased over time	[SeIV/Se] = 0.053 - 0.024 week	0.544	p<0.02
• [root Se] increased with [shoot Se]	[root Se] = -10.86 + 4.09 [shoot Se]	0.747	p<0.003
• shoot [Se] did not change over time			
• root Se did not change over time			

Significant linear regression relationships ($p<0.05$) for **brass buttons** measurements 6/23 - 10/15/95. vol rate = selenium volatilization rate (µg Se m^{-2} day^{-1}); [SeIV] = dissolved selenite concentration (µg SeIV L^{-1}) in sediment pore water; [shoot Se] = total selenium concentration (mg Se kg^{-1} dw) in shoot tissue; [root Se] = total selenium concentration (mg Se kg^{-1} dw) in root tissue.

Relationship	**Regression Equation**	**r^2**	**Significance**
• volatilization increased when pore-water [SeIV] increased	vol rate = -0.69 + 23.74[SeIV]	0.459	$p<0.02$
• shoot [Se] did not change over time			
• root Se did not change over time			

Significant ($p<0.05$) linear regression relationships for **saltgrass** measurements 6/23 - 10/15/95. vol rate = selenium volatilization rate (µg Se m^{-2} day^{-1}); [Se] = total dissolved selenium concentration (µg Se L^{-1}) in sediment pore-water; [SeIV] = dissolved selenite concentration (µg SeIV L^{-1}) in sediment pore water; EC = electrical conductivity (µS); Eh = redox potential (mV); [shoot Se] = total selenium concentration (mg Se kg^{-1} dw) in shoot tissue; [root Se] = total selenium concentration (mg Se kg^{-1} dw) in root tissue;

Relationship	Regression Equation	r^2	Significance
• volatilization increased when pore-water [Se] increased	vol rate = -10.54 + 6.81 Se	0.359	p<0.04
• volatilization increased when [SeIV/Se] increased	vol rate = 88.83 - 93.25 SeIV/Se	0.530	p<0.007
• volatilization decreased when EC increased	vol rate = 194.3 - 0.032 EC	0.435	p<0.02
• volatilization decreased when Eh increased	vol rate = 118.0 - 0.70 Eh	0.655	p<0.01
• pore-water [Se] increased over time	Se = 4.37 + 0.48 week	0.341	p<0.05
• pore-water [SeIV/Se] decreased over time	SeIV/Se = 0.857 - 0.051 week	0.486	p<0.01
• shoot [Se] did not change over time			
• root Se did not change over time			

Significant linear regression relationships ($p<0.05$) for **rabbitfoot grass** measurements 6/23 - 10/15/95. [shoot Se] = total selenium concentration (mg Se kg^{-1} dw) in shoot tissue; [root Se] = total selenium concentration (mg Se kg^{-1} dw) in root tissue; [Se] = total dissolved selenium concentration (µg Se L^{-1}) in sediment pore-water; [SeIV] = dissolved selenite concentration (µg SeIV L^{-1}) in sediment pore water.

Relationship	**Regression Equation**	**r^2**	**Significance**
• shoot [Se] increased when pore-water [Se] increased	shoot Se = -0.41 + 0.85 Se	0.616	p<0.003
• pore-water [Se] increased over time	Se = 0.5 + 0.93 week	0.563	p<0.005
• pore-water [SeIV/Se] decreased over time	SeIV/Se = 0.584 - 0.027 week	0.494	p<0.01
• shoot [Se] did not change over time			
• root [Se] increased over time	root Se = 7.43 + 1.33 week	0.332	p<0.05

Summary of mean values (± standard deviation) for water chemistry parameters measured by UC Berkeley in Pass 1 inlet and outlet waters 6/23 - 10/13/95. [Se] & [SeIV] = total dissolved selenium and dissolved selenite concentrations, (µg Se L^{-1}), respectively; Se & Se IV (mass) = total dissolved Se and dissolved Se IV mass-flux per day (g Se day^{-1}), respectively;
EC = electrical conductivity (µS) ; Eh = redox potential (mV).

Parameter Measured	**Mean ± Standard Deviation**
• Inlet total [Se]	23.0 ± 6.4
• Outlet total [Se]	7.5 ± 4.0
• Inlet [SeIV]	18.3 ± 6.9
• Outlet [SeIV]	4.6 ± 2.5
• Inlet Se (mass)	150.6 ± 57
• Outlet Se (mass)	54 ± 36
• Inlet Se IV (mass)	119.8 ± 57.7
• Outlet Se IV (mass)	33.2 ± 24
• Inlet pH	7.34 ± 0.22
• Outlet pH	7.31 ± 0.19
• Inlet EC	3560 ± 680
• Outlet EC	3950 ± 670
• Inlet Eh	81.5 ± 52
• Outlet Eh	89.2 ± 42.4
• Inlet % SeIV/Se	82.1 ± 36
• Outlet % SeIV/Se	65.9 ± 20
• % change in SeIV/Se	14.4 ± 30
• % [Se] removed	68.9 ± ± 11
• % [SeIV] removed	72.6 ± 17
• Inlet Se mass - Outlet Se mass	96.6 ± 41.8
• Inlet Se IV mass - Outlet Se IV	86.5 ± 47
• % mass Se removed	65.7 ± 15.4
• % mass Se IV removed	70.4 ± 20.4

Summary of regression analyses with time for water chemistry parameters on a concentration basis. Parameters sampled by UC Berkeley in Pass 1 of the San Francisco Bay wetland (6/23 - 10/13/95). [Se] & [SeIV] = total dissolved selenium and dissolved selenite concentrations, (µg Se L^{-1}), respectively; respectively; EC = electrical conductivity (µS) ; Eh = redox potential (mV).

Relationship	**Regression Equation**	**r^2**	**Significance**
• Inlet [Se] increased over time	Se = 14.63 + 0.99 week	0.54	$p<0.001$
• Outlet [Se] increased over time	Se = 1.58 + 0.70 week	0.69	$p<0.0001$
• Inlet [Se IV] changed over time	$\text{Se IV} = 6.84 + 3.81\ \text{week} - 0.22\ \text{week}^2$	0.40	$p<0.04$
• Outlet [Se IV] increased over time	Se IV = 1.81 + 0.33 week	0.40	$p<0.01$
• Inlet pH increased over time	pH = 7.11 + 0.03 week	0.34	$p<0.02$
• Outlet pH did not change over time			
• Inlet EC decreased over time	EC = 4546.5 - 116.5 week	0.67	$p<0.0001$
• Outlet EC decreased over time	EC = 5022.8 - 125.7 week	0.34	$p<0.0001$
• Inlet Eh decreased over time	$\text{Eh} = 420.3 - 58.9\ \text{week} + 2.29\ \text{week}^2$	0.79	$p<0.005$
• Outlet Eh decreased over time	$\text{Eh} = 397.1 - 56.9\ \text{week} + 2.37\ \text{week}^2$		
• Inlet %[SeIV] decreased over time	% SeIV = 110.9 - 3.39 week	0.39	$p<0.01$
• Outlet % [Se IV] did not change over time			
• [Se] removed did not change over time			
• [Se IV] removed changed over time	$7.0 + 2.83\ \text{week} - 0.19\ \text{week}^2$	0.41	$p<0.02$
• % [Se] removed decreased over time	% Se removed = 83.03 - 1.66 week	0.51	$p<0.002$
• % [SeIV] removed decreased over time	%SeIV removed = 94.04 - 2.5 week	0.52	$p<0.002$

Summary of regression analyses with time for selenium mass-fluxes based on UC Berkeley measurements for San Francisco Bay wetland Pass 1 inlet and outlet waters 6/23 - 10/13/95. Se and SeIV (mass) = total dissolved selenium (Se) and dissolved selenite (Se IV) mass-fluxes (g Se day^{-1}), respectively.

Relationship	**Regression Equation**	**r^2**	**Significance**
• Inlet Se (mass) changed over time	$8.8 + 34.04\ \text{week} - 1.58\ \text{week}^2$	0.65	$p<0.001$
• Inlet Se IV (mass) changed over time	$1.12 + 36.67\ \text{week} - 2.06\ \text{week}^2$	0.51	$p<0.01$
• Outlet Se (mass) increased over time	$9.83 + 5.19\ \text{week}$	0.47	$p<0.003$
• Outlet Se IV (mass) increased over time	$10.65 + 2.66\ \text{week}$	0.28	$p<0.04$
• Se (mass) removed changed over time	$10.17 + 25.12\ \text{week} - 1.36\ \text{week}^2$	0.46	$p<0.02$
• Se IV (mass) removed changed over time	$8.32 + 28.06\ \text{week} - 1.7\ \text{week}^2$	0.52	$p<0.004$
• % Se (mass) removed decreased over time	$81.33 - 1.83\ \text{week}$	0.32	$p<0.02$
• % Se IV (mass) decreased over time	$94.59 - 2.85\ \text{week}$	0.44	$p<0.005$

Summary of mean values (± standard deviation) for water chemistry parameters measured by UC Berkeley in sediment pore water at the primary study site in Pass 1 of the San Francisco Bay wetland 6/23 - 10/13/95. [Se] & [SeIV] = total dissolved selenium and dissolved selenite concentrations, respectively (µg Se L^{-1}); EC = electrical conductivity (µS); Eh = redox potential (mV).

Parameter Measured	**Mean ± Standard Deviation**
• Pore water [Se]	6.3 ± 3.9
• Pore water [Se IV]	1.6 ± 0.8
• Pore water pH	7.21 ± 0.21
• Pore water EC	6869 ± 4394
• Pore water Eh	75 ± 47
• Pore water % Se IV	33 ± 18

Summary of regression analyses with time for water chemistry parameters measured by UC Berkeley in sediment pore water at the primary study site in Pass 1 of the San Francisco Bay wetland 6/23 - 10/13/95. [Se] & [SeIV] = total dissolved selenium and dissolved selenite concentrations, respectively (µg Se L^{-1}); EC = electrical conductivity (µS) ; Eh = redox potential (mV).

Relationship	**Regression Equation**	**r^2**	**Significance**
• [Se] increased over time	[Se] = 2.12 + 0.47 week	0.31	$p<0.0001$
• [Se IV] did not change over time			
• pH did not change over time			
• EC did not change over time			
• Eh decreased over time	Eh = 157.84 - 7.99 week	0.33	$p<0.0001$
• % [Se IV] decreased over time	% [Se IV] = 54.83 - 2.48 week	0.42	$p<0.0001$

F

CODES FOR RAW DATA FROM UC BERKELEY

Set II Primary Spreadsheet

(pages entitled: “All Vol”)

Column explanation:

sample # - coded as: “species initial. chamber number. week. replicate”, where species initial: s =*Scirpus*; d = *Distichlis*; c = *Cotula*; v = v-ditch (inlet channel); p = *Polypogon*; t = *Typha*; chamber number = 1 - 6; week = week of measurement (1 - 16); and replicate = first or second measurement during the week (a,b, etc.; weeks 5 - 16 only).

dates - dates of measurement (1995)

species - species initial code (see above)

#days - length of measurement in days

week - week of measurement (1 - 16)

vol rate - results of volatilization trap analyses, expressed as µg Se volatilized m^{-2} d^{-1}.

Se-G - results of sediment pore water analyses for total dissolved Se, expressed as µg Se L^{-1}.

SeIV-G - results of sediment pore water analyses for dissolved selenite, expressed as µg Se IV L^{-1}.

pH - pH of sediment pore water samples.

EC - electrical conductivity of sediment pore water samples (µS).

ORP - redox potential of sediment pore water samples (mV).

wat ht - water height at volatilization chamber location (to nearest inch).

Se-S -	results of analyses for total dissolved Se in water samples taken at the surface water/sediment interface (weeks 11 & 12 only), expressed as µg Se L^{-1}.
SeIV-S -	results of analyses for dissolved selenite in water samples taken at the surface water/sediment interface (weeks 11 & 12 only), expressed as µg Se IV L^{-1}.
pH-S -	pH of water samples taken at the surface water/sediment interface (weeks 11 & 12 only).
EC-S -	electrical conductivity (µS) of water samples taken at the surface water/sediment interface (weeks 11 & 12 only).
ORP-S -	redox potential (mV) of water samples taken at the surface water/sediment interface (weeks 11 & 12 only).
shoot Se -	results of shoot-tissue analyses, expressed as mg Se kg^{-1} dw.
root Se -	results of root-tissue analyses, expressed as mg Se kg^{-1} dw

Set I Primary Spreadsheet

(pages entitled: “prelim vol data”)

Column explanation:

sample# -	coded as “chamber number.measurement”.
site -	site description
group site -	groups similar sites
veg or non -	vegetated (v) or nonvegetated (n) site designation
dates -	dates of measurement (1995)
#days -	length of measurement in days
vol rate -	results of volatilization trap analyses, expressed as µg Se volatilized m^{-2} d^{-1}.
SeIV -	estimate of pore water selenite concentration (µg Se IV L^{-1}).
vr -	same as vol rate
adj SeIV -	same as SeIV, less questionable samples.

Sediment Analyses Primary Spreadsheet

(pages entitled: “raw soil data”)

Column explanation:

sample#-	coded as “species-site initial. chamber number. week” (same as described above).
month -	first (1), or fourth (4), four-week period sample was taken.
species -	species initial, described above.
zone -	grouping of sediment samples by location, as opposed to grouping by species.
aa ppb -	concentration of Se in samples analyzed (µg Se L^{-1}).
ppm Se -	actual concentration of Se in sediment samples (mg Se kg^{-1} dw).

Mean Daily Temperatures Inside and Outside Volatilization Chambers

(pages entitled: “grouped daily means by week”)

Column explanation:

date -	(day-month-year)
week -	week of measurement (1 -16)
day -	day of measurement (1 -112)
n -	number of measurements for that day
out temp -	mean daily temperature (°C) outside volatilization chambers at mean plant height.
in temp -	mean daily temperature (°C) inside volatilization chambers at mean plant height.
in-out -	the difference between inside and outside temperatures (inside temperature - outside temperature).

UC Berkeley Pass 1 Water Determinations Primary Spreadsheet (Concentration)

(pages entitled: “in/out water data”)

Column explanation:

date-	date of sample (1995).
week -	week of sample (1 -16).
out# -	Pass 1 outlet sample code: outlet.week of measurement. replicate
out Se -	results of analyses for total dissolved Se (µg Se L^{-1}) in Pass 1 outlet waters.
out SeIV -	results of analyses for dissolved selenite (µg SeIV L^{-1}) in Pass 1 outlet waters.
out pH -	pH of outlet water sample
out EC -	electrical conductivity of outlet water sample (µS).
out ORP -	redox potential of outlet water sample (mV).
in Se -	results of analyses for total dissolved Se (µg Se L^{-1}) in Pass 1 inlet waters.
in SeIV -	results of analyses for dissolved selenite (µg SeIV L^{-1}) in Pass 1 inlet waters.
in pH -	pH of inlet water sample
in EC -	electrical conductivity of inlet water sample (µS).
in ORP -	redox potential of inlet water sample (mV).
in %SeIV -	percent selenite in Pass 1 inlet waters (inlet Se/inlet SeIV) × 100.
o%SeIV -	percent selenite in Pass 1 outlet waters (outlet Se/outlet SeIV) × 100.
%change -	percent change in percent selenite between Pass 1 inlet and Pass 1 outlet waters (1- (out %SeIV/in %SeIV) × 100.
in-out -	the difference between Pass 1 inlet and outlet total dissolved Se concentrations (µg Se L^{-1}).

in4-out4 -	the difference between Pass 1 inlet and outlet dissolved selenite concentrations (µg Se IV L^{-1}).
in pH-out pH -	the difference between Pass 1 inlet and outlet water pH.
i EC-o EC -	the difference between Pass 1 inlet and outlet ECs (µS).
iORP-oORP -	the difference between Pass 1 inlet and outlet water redox potentials (mV).
%Se removed -	the percent total dissolved Se concentration removed by Pass 1 (1-(outSe/inSe) × 100.
%SeIV removed -	the percent dissolved Se IV concentration removed by Pass 1 (1-(outSeIV/inSeIV) × 100.
inSe/outSe -	the ratio of inlet total dissolved Se to outlet total dissolved Se (inlet Se/outlet Se).
inSeIV/outSeIV -	the ratio of inlet dissolved SeIV to outlet dissolved SeIV (inlet SeIV/outlet SeIV).

UC Berkeley Pass 1 Water Determinations Primary Spreadsheet (Mass)

(pages entitled: “ucb mass in/out data”)

Column explanation:

week - week of measurement (1 - 16).

period - divides data into four 4-week periods.

2 periods - divides data into two 8-week periods.

in Se - Pass 1 inlet total dissolved Se concentration (µg Se L^{-1}).

out Se - Pass 1 outlet total dissolved Se concentration (µg Se L^{-1}).

in SeIV - Pass 1 inlet dissolved SeIV concentration (µg SeIV L^{-1}).

out SeIV - Pass 1 outlet dissolved SeIV concentration (µg SeIV L^{-1}).

in flow - Pass 1 inlet weekly mean flow rate (million gallons day^{-1}).

out flow - Pass 1 outlet mean flow rate (million gallons day^{-1}).

mass in - mass-flux of total dissolved Se into Pass 1 (g Se day^{-1}).

mass out - mass-flux of total dissolved Se out of Pass 1 (g Se day^{-1}).

mass4 in - mass-flux of dissolved SeIV into Pass 1 (g SeIV day^{-1}).

mass4 out - mass-flux of dissolved SeIV out of Pass 1 (g SeIV day^{-1}).

in-out - mass of total dissolved Se removed by Pass 1 (inlet Se mass - outlet Se mass) (g Se day^{-1}).

in4-out4 - mass of dissolved SeIV removed by Pass 1 (inlet SeIV mass - outlet SeIV mass) (g SeIV day^{-1}).

%removed - percentage of the inlet mass of total dissolved Se removed by Pass 1 (1-(outlet Se mass/inlet Se mass) × 100.

%4removed - percentage of the inlet mass of dissolved SeIV removed by Pass 1 (1-(outlet SeIV mass/inlet SeIV mass) × 100.

G

SUMMARY OF DATA FROM CHEVRON

Summary of mean values (± standard deviation) for total selenium concentration(μg Se L^{-1}), water flow rates (10^6 L day^{-1}), and corresponding mass-fluxes (g Se day^{-1}) measured by Chevron for Pass 1 inlet and outlet and Pass 3 outlet waters 6/23 - 10/13/95.

Parameter Measured	Mean
Inlet total [Se]	25.8 ± 5
Outlet total [Se] (Pass 1)	8.0 ± 3.2
Outlet total [Se] (Pass 3)	4.5 ± 0.6
Inlet flow	6.37 ± 1.40
Outlet flow (Pass 1)	6.78 ± 3.01
Outlet flow (Pass 3)	3.85 ± 0.65
Inlet Se (mass)	167.6 ± 52.9
Outlet Se (mass) (Pass 1)	55.2 ± 25.5
Outlet Se (mass) (Pass 3)	17.3 ± 2.2
% [Se] removed (Pass 1)	68.8 ± 12.1
% [Se] removed (Entire wetland)	82.4 ± 4.3
% Se mass removed (Pass 1)	66.6 ± 14.1
% Se mass removed (Entire wetland)	89.1 ± 3.8
Inlet mass - outlet mass (Pass 1)	112.4 ± 42.8
Inlet mass - outlet mass (Entire wetland)	155.6 ± 49.5

Summary of regression analyses with time for determinations made by Chevron for Pass 1 inlet and outlet and Pass 3 outlet waters 6/23-10/13/95. [Se] = total dissolved selenium concentration (µg Se L^{-1}); flow = mean water flow rate (10^6 L day^{-1}); Se (mass) = mass-flux (g Se day^{-1}).

Relationship	**Regression Equation**	**r^2**	**Significance**
Inlet flow changed over time	flow = 3.51 + 0.76 week - 0.04 $week^2$	0.36	$p<0.0001$
Pass 1 Oulet flow did not change over time			
Pass 3 Outlet flow did not change over time			
Inlet [Se] did not change over time			
Pass 1 Outlet [Se] increased over time	[Se] = 3.33 + 0.55 week	0.69	$p<0.0001$
Pass 3 Outlet [Se] did not change over time			
[Se] removed (Pass 1) changed over time	[Se] = 13.68 + 2.1 week - 0.15 $week^2$	0.50	$p<0.01$
[Se] removed (Entire wetland) did not change over time			
Inlet Se (mass) changed over time	Se = 57.87 + 31.45 week - 1.69 $week^2$	0.45	$p<0.02$
Pass 1 Outlet Se (mass) increased over time	Se = 18.89 + 4.27 week	0.63	$p<0.0002$
Pass 3 Outlet Se (mass) did not change over time			
Se removed (mass) (Pass 1) changed over time	Se = 41.88 + 26.22 week - 1.63 $week^2$	0.58	$p<0.004$
Se removed (mass) (Entire wetland) did not change over time			
% [Se] removed (Pass 1) decreased over time	Se = 76.68 + 1.3 week - 0.2 $week^2$	0.79	$p<0.0001$
% [Se] removed (Entire wetland) did not change over time			
% Se removed (mass) (Pass 1) decreased over time	Se = 70.6 + 3.09 - 0.32 $week^2$	0.86	$p<0.0001$
% Se removed (mass) (Entire wetland)	79.62 + 2.58 week - 0.14 $week^2$	0.40	$p<0.05$

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CODES FOR RAW DATA FROM CHEVRON

Flow-Rate Primary Spreadsheet, Data Provided by Chevron

(pages entitled: “chev marsh flo rates”)

Column explanation:

date -	date of measurement (1995).
week -	week of measurement (1 -16).
period -	divides the data into two 8-week periods.
pds 1-4 -	divides the data into four 4-week periods.
mgal in -	flow rate into Pass 1, read from calibrated weir (million gallons day^{-1}).
D height -	change in water height in Pass 1 since last observation (inches).
D mgal -	change in water height converted to volume (1 inch = 0.75 million gallons)
mgal out -	flow rate out of Pass 1 = (mgal in Pass 1 - D mgal) (million gallons day^{-1}).
out 3rd -	flow rate out of Pass 3, read from gauge on pump (million gallons day^{-1}).
mL in -	flow rate into Pass 1 (10^6 L day^{-1}).
mL out -	flow rate out of Pass 1 (10^6 L day^{-1}).
mL out3 -	flow rate out of Pass 3 (10^6 L day^{-1}.

Chevron Water Determinations Primary Spreadsheet

(pages entitled: “chev mass data”)

Column explanation:

week - week of measurement (1-16).

period - divides the data into two 2-week periods.

4 periods - divides the data into four 4-week periods.

n - number of flow rate estimates for that week.

in 1st flo - water flow rate into Pass 1 (million gallons day^{-1}).

in 1st ppb - Pass 1 inlet total Se concentration (µg Se L^{-1}).

in 1st grams - mass-flux into Pass 1 (g Se day^{-1}).

out 1st flo - water flow rate out of Pass 1 (million gallons day^{-1}).

out 1st ppb - Pass 1 outlet total Se concentration (µg Se L^{-1}).

out 1st grams - mass-flux out of Pass 1 (g Se day^{-1}).

out 3rd flo - water flow rate out of Pass 3 (million gallons day^{-1}).

out 3rd ppb - Pass 3 outlet total Se concentration (µg Se L^{-1}).

out 3rd grams - mass-flux out of Pass 3 (g Se day^{-1}).

%mass rem1 - the percentage of the inlet mass removed by Pass 1 (1-(out 1st grams/in 1st grams) × 100.

%mass rem3 - the percentage of the inlet mass removed by the entire wetland (1-(out 3rd grams/in 1st grams) × 100.

%conc rem1 - the percentage of the inlet total Se concentration removed by Pass 1 (1-(out 1st ppb/in 1st ppb) × 100.

%conc rem3 - the percentage of the inlet total Se concentration removed by the entire wetland (1-(out 3rd ppb/in 1st ppb) × 100.

grams rem1 - mass of total Se removed by Pass 1 (in 1st grams - out 1st grams) (g Se day^{-1}).

grams rem3 - mass of total Se removed by the entire wetland (in 1st grams - out 3rd grams) (g Se day^{-1}).

conc rem1 - the difference between Pass 1 inlet and outlet total Se concentrations (µg Se L^{-1}).

conc rem3 - the difference between Pass 1 inlet and Pass 3 outlet total Se concentrations (µg Se L^{-1}).

Target:
Facilities Water Management

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