1997

Assessment of selenium concentrations in ephemeral pools at Kesterson Reservoir

Brandolyn Maltese Patterson
San Jose State University

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**ASSESSMENT OF SELENIUM CONCENTRATIONS IN
EPHEMERAL POOLS
AT
KESTERSON RESERVOIR**

**A Thesis
Presented To
The Department Of Environmental Studies
San José State University**

**In Partial Fulfillment
of the Requirements for the Degree
Master Of Science**

**by
Brandolyn Maltese Patterson**

December 1997

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APPROVED FOR THE DEPARTMENT OF ENVIRONMENTAL STUDIES

Dr. Lynne Trulio, Associate Professor of Environmental Studies
Committee Chairperson

Dr. Karina Garbesi, Assistant Professor of Environmental Studies

Dr. Tetsu Tokunaga, Staff Geological Scientist

APPROVED FOR THE UNIVERSITY

ABSTRACT

TITLE: Assessment of Selenium Concentrations In Ephemeral Pools At Kesterson Reservoir

INVESTIGATOR: Brandolyn Maltese Patterson **TELEPHONE:** (209)667-2184

ADDRESS: 1620 Stuart Place, Turlock, CA 95382

PROJECT DURATION: September 1996 - November 1997 **BUDGET:** \$3094.15

The dilemma of what to do with agricultural drain water laden with salts, selenium, and other potentially toxic compounds has grown over the last 40 years and will continue to grow as a result of large-scale irrigation in California's Central Valley.

The results of selenium exposure and bioaccumulation were illustrated at Kesterson Reservoir in 1983 to 1986. It has been established that high levels of selenium previously found in ponds at Kesterson Reservoir were toxic to plants, animals, and humans. Monitoring, of the selenium concentration in ephemeral pools, is necessary to determine the exposure levels to which aquatic species and wildlife are exposed.

This study used historical records and newly acquired field data to assess the seasonal variation in ephemeral pool selenium concentrations during the period 1989-1997. Water samples from eight ephemeral pools were taken at four time intervals from December to March (the "wet" season), 1997, and analyzed for total selenium. High concentrations ($p = 3.9 \times 10^{-7}$) were found early in the season (December/January), with concentrations decreasing significantly thereafter. At the beginning of the season, 93% of the pools had a selenium concentration above the wildlife safety standard of 2-5 ug/l; at the end of the season 75% of the pools still exceeded this goal.

This study also attempted to determine if selenium concentrations in the pools were changing with each successive season. Data collected by other researchers was not consistent enough to be analyzed for this purpose. Recommendations are made on how to gather sufficient data to perform a multi-year analysis.

Key words: selenium, agricultural drain water, Kesterson Reservoir, bioaccumulation

ACKNOWLEDGEMENTS

I would like to extend a special thank you to Dr. Lynne Trulio for all of her time and patience spent in helping me to complete this project, to Dr. Karina Garbesi for her thorough and rapid review of my methods section, and to Dr. Tetsu Tokunaga of Lawrence Berkeley National Laboratories for his suggestions and valuable input.

I would also like to thank Dr. Linda Gillispie for sparking my interest in a study of Kesterson.

And, I wish to thank my parents, Frances L. and Jack D. Patterson, and to my brother, Sean Maltese Patterson, for their numerous trips out to Kesterson Reservoir, for listening to me talk about Kesterson at nauseam, and for their endless support.

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INTRODUCTION

Selenium is a naturally-occurring element that is necessary in the metabolism of humans and livestock in very small quantities, but is toxic in larger amounts (Presser and Ohlendorf 1987; Alemi 1988). Selenium can be released into the environment by both anthropogenic and natural processes. Anthropogenic processes include metal refining and smelting (Horne 1991) and the combustion of fossil fuels (Bennett et al. 1986). Natural weathering processes cause the slow release of selenium from sediments (Alemi 1988) and shale deposits containing selenite (Bertine and Goldberg 1971; National Research Council 1976).

Selenium in the San Joaquin Valley of Central California was deposited during the Cretaceous period and is thought to have been exposed as seleniferous pyrite seams were uplifted and oxidized. Surface runoff and percolating water then transported the selenium to the valley floor (Coppock 1987; Alemi et al. 1988; Alemi 1988).

In the mid-19th century, the natural weathering processes of selenium in the California Central Valley were disrupted by the introduction of tile drainage systems, clay tiles or plastic tubes placed 6 to 10 feet under the soil that allow excess water and excess salts to drain away from plant roots, and the use of agricultural irrigation on a larger scale. When an area containing selenium is irrigated for agriculture, the element is leached from the soil at a more rapid rate than would occur by natural weathering processes. The leached selenium is then carried away from the area in agricultural drain water.

Since the introduction of tile drainage systems to the California Central Valley, the amount of agricultural drain water requiring disposal has steadily increased. In 1986, 15,000 to 16,000 ac-ft of agricultural drain water from the California Central Valley required disposal at Kesterson Reservoir, due to high selenium concentrations (Benson et al. 1992). Benson et al. (1992) predict that the amount of agricultural drain water that will require disposal in the future could reach 170,000 ac-ft per year by 2015 and up to 668,000 ac-ft per year by 2085.

Selenium concentrations increase as agricultural water drained from the field is consolidated in one location and allowed to concentrate through water evaporation. The creation of the San Luis Drain was thought to be the solution to the problem of agricultural drain water disposal in the Central Valley. This enormous drain was designed to carry agricultural drain water from the San Joaquin Valley to the Sacramento Delta. As part of the drain, a flow regulating reservoir was to be built at its mid-point. Kesterson Reservoir, built on grasslands within Kesterson National Wildlife Refuge, in Merced County, California, was designed to meet this objective. The Reservoir was composed of twelve, unlined ponds through which drain water flows could be regulated. However, the San Luis Drain project was never fully completed and Kesterson Reservoir, which was originally intended to be a flow-regulating reservoir, became a series of terminal evaporation ponds (Coppock 1987) (Figure 1 and Figure 2).

Figure 1. Location of Kesterson Reservoir in California.

Figure 2. Photograph of Kesterson Reservoir prior to dewatering in 1986.
Photograph taken from Resources at Risk, UC Agricultural Issues Center, UC Davis.

Two years after Kesterson Reservoir (Kesterson) was established, high selenium concentrations were found in the drainage water (Ohlendorf et al. 1988; Presser and Ohlendorf 1987; Horne 1991; Benson et al. 1992). This finding was followed by studies showing that exposure to water with high selenium concentrations is detrimental to aquatic organisms (Presser and Ohlendorf 1987; U.S. EPA 1987; Benson et al. 1992), waterfowl (Ohlendorf et al. 1986; Heinz et al. 1987; Benson et al. 1992) and other wildlife (Heinz et al. 1987; Benson et al. 1992). Studies conducted by Bennett et al. (1986), Schuler (1987), and Alemi (1988) have also shown that selenium bioaccumulates and moves up the food chain.

As a result of these discoveries, Kesterson has not accepted drain water since 1986, and ponds dewatered through evaporation and seepage. Yet, due to the mixing of some soluble selenium from the contaminated soils into rainfall generated pools, and seasonal rise in water table elevations, high selenium concentrations are still present in ephemeral (seasonal) pools on the site (Tokunaga et al. 1991; Tokunaga and Benson 1992; Zawislanski et al. 1995).

Through the ephemeral pools and underlying sediments, aquatic organisms and waterfowl are exposed to selenium and bioaccumulation effects (Benson et al. 1992; Poister and Tokunaga 1992). One individual organism at the bottom of the food web may not contain a toxic level of selenium in its body. But, because selenium can build up in an organism, when this organism is consumed by other organisms higher up the food chain, the selenium is passed on to the next organism. In this manner,

selenium can build up in an organism until it reaches a harmful, or even toxic, level. Increased exposure to selenium will lead to an increase in the amount of selenium accumulating in individuals lower in the food web and, therefore, poses an increased risk to organisms higher up in the food web (Ohlendorf et al. 1988; Bennett et al. 1986; Alemi 1988; Schuler 1987).

Over the past 11 years (1986-1997), numerous studies have been conducted on the selenium levels at Kesterson. Selenium levels in ephemeral pools have been a topic of particular interest. Ephemeral pools formed by water table rise have been investigated in the field (Tokunaga and Benson 1992). Tokunaga and Benson (1992) showed that soil solutions containing selenium can be pushed to the surface by a rising, shallow water table. In addition, Tokunaga and Benson (1992) demonstrated that soils with a total selenium concentration less than the 4 mg/kg remediation goal were capable of producing pools containing high levels of water soluble selenium. Therefore, the removal of selenium laden surface soils is not an accurate nor effective remediation method to be used in controlling ephemeral pool selenium concentrations when subsoils contain high concentrations of soluble selenium. Laboratory studies focusing on transport and absorption of selenium have also been carried out (Poister and Tokunaga 1992; Alemi et al. 1988; Neal et al. 1987). These studies have identified the correlation of selenium level in ephemeral pool waters and: the amount of water-extractable soil selenium, pH, soil ionic composition, and velocity of the water table rise.

Ground water and ephemeral pool water monitoring programs have been conducted by the United States Bureau of Reclamation (USBR) and Lawrence Berkeley National Laboratory (LBNL). USBR ephemeral pool monitoring program consists of 6 years (1989-1996) of sample records, containing selenium data collected throughout the wet season (approximately December to March) from pools in each of the 12 ponds. This program does not contain a statistical analysis of the data collected. LBNL studies at Kesterson have been concerned with selenium oxidation and reduction, speciation, and spatial distribution. Findings from LBNL have found that pool selenium concentrations vary during the season.

No statistical analysis of USBR (1987-1996) and LBNL (1992-1994) ephemeral pool monitoring data has been conducted to determine if, in fact, the pool selenium concentrations do vary significantly within the season and from year-to-year. It would be valuable to determine if the USBR (1987-1996) data concur with those previously gathered by LBNL. Improved knowledge of seasonal variations in selenium concentration could potentially effect sampling time schemes, as well as laboratory investigations in bioaccumulation that attempt to model conditions at Kesterson. Year-to-year analysis, to determine if selenium levels are increasing, decreasing, or stabilizing, are very important in developing future management strategies.

OBJECTIVES

Selenium has a complex chemical cycle. Because of this, the amount of biologically available selenium within the soil and ephemeral pools at Kesterson has the potential to change over time. The objectives of this study were to assess the changes in mobile selenium levels in the ephemeral pools at Kesterson over time and to determine the current selenium concentrations to which organisms are being exposed. Specifically, the following questions were addressed:

1. Do the selenium concentrations in the ephemeral pools vary within a single season, and, if so, what is the trend?
2. Are the selenium concentrations in the ephemeral pools changing with each successive season, and if so, what is the pattern?
3. Do the waters in the ephemeral pools currently meet the wildlife remediation goal of less than 2-5 ug/l selenium?

Answers to these questions at Kesterson provide important information on how selenium concentrations in ephemeral pools may vary within and between seasons. Variations in selenium concentration would mean that exposure levels, rates of up-take, and up-take levels would also vary. How and to what extent these variations occur are factors in calculating the rate of bioaccumulation in the food chain.

Quantifying changes in selenium levels in ephemeral pools over a longer time period, perhaps 15 to 20 years, is critical to predicting the long-term biological effects of this system, as well as developing an appropriate management strategy for the future.

RELATED RESEARCH

The primary foci of this study were to quantify the amount of selenium currently present in ephemeral pool waters at Kesterson and to determine if significant changes in concentration take place within a season and between seasons. Therefore, selenium soil chemistry, effects of selenium on aquatic species and waterfowl, and any previous Kesterson ephemeral pool studies are important for understanding the context, implications, and importance of this study. Investigation of these three topics provides sufficient background to understand the previously stated "objective questions" and to be able to interpret findings in light of the current body of available literature.

Selenium Soil Chemistry

In nature, selenium exists in a variety of states, including selenide (-II), elemental selenium (0), selenite (IV), selenate (VI), and organic compounds (Adriano 1986). Inorganic selenium is most mobile (i.e. water soluble and bioavailable) in the (IV) and (VI) states (Adriano 1986). Elemental forms are generally insoluble and, therefore, biologically unavailable (Weres et al. 1985). Many organo-selenium compounds are very bioavailable and toxic. A more detailed explanation of these chemical states occurs below.

The processes that render soil selenium mobile or immobile are not completely understood. Mobilization and adsorption of selenium in the soil are believed to be

controlled primarily by oxidation-reduction reactions (Long et al. 1990). Other factors, including the presence of Fe, Mn, Al, and a low pH level, tend to discourage the formation of water soluble selenium (Neal et al. 1987; Long et al. 1990; Weres et al. 1995). Porous alkaline soils, such as those found in the San Joaquin Valley (Presser and Ohlendorf 1987; Alemi et al. 1988), allow for the oxidation of selenite (Se(IV)) to selenate (Se (VI)) (Alemi 1988; Long et al. 1990), both of which are mobile in the soil; therefore, able to be transported in the water and used in biological processes (Adriano 1986; Presser and Ohlendorf 1987; Alemi et al. 1988). Selenate is rarely found in mildly reducing conditions, such as when an area is flooded, or in the presence of H_2S or Fe(II). Microbial activity can reduce selenium to organic and elemental forms under anaerobic conditions (Weres et al. 1985).

During the period 1981-1986, an estimated 9,000 kg of selenium, mostly as selenate (Se(VI)), were carried to Kesterson Reservoir by agricultural drain water via the San Luis Drain (Presser and Ohlendorf 1987; Ohlendorf et al. 1988; Long et al. 1990; Tokunaga et al. 1991). In 1986, dumping of drain waters into Kesterson ceased and the existing surface water was allowed to infiltrate and evaporate, leaving the selenium and salts behind (Tokunaga et al. 1991). Currently, the top 15 cm of the soil in unfilled areas at Kesterson are believed to contain 75% of the selenium delivered to the system (Tokunaga et al. 1991). The United States Bureau of Reclamation (USBR) found average soil selenium levels to be 5 mg/kg with a range of 1 to 100 mg/kg. The (USBR) remediation goal was set at 4 mg/kg. Wahl, Benson,

and Santolo (1994) estimate that 93% of the soil selenium is now immobile, with the potential for future remobilization, to Se(IV) and Se(VI), as oxidation occurs. Soil solutions were found to contain selenium (IV and VI) concentrations up to 1,000 ug/l (Tokunaga et al. 1991; Tokunaga and Benson 1992). Wildlife species are very sensitive to this element. The surface water goal for selenium is 2 to 5 ug/l; levels above this are considered harmful. The EPA drinking water standard is slightly higher at 10 ug/l for humans.

Because aqueous concentrations of selenium that exceed 5 ug/l are toxic to animal life (Presser and Ohlendorf 1987; Benson et al 1992; U.S. EPA 1987; Bennett et al. 1986), many experiments have been conducted examining how to eliminate selenium from Kesterson Reservoir and/or to determine which conditions will permanently immobilize selenium in the soil. Volatilization, excavation, and vegetative growth extraction processes have been proposed as ways to eliminate the selenium from the soil. However, these methods are time consuming and have shown limited success (Horne 1991). Long et al. (1990) and Horne (1991) have investigated the use of a permanent flooding technique (with nonseleniferous waters) to lessen the entry of selenium into the food chain by establishing permanently reducing conditions. After flooding, a sharp increase in the soil water total selenium concentration was found (Long et al. 1990), followed by a decline in soil water selenium concentrations. It is believed that reducing conditions had been established, resulting in the selenium being immobilized, not water soluble or biologically available (Long et al. 1990). Horne's

study (1991) also showed decreases in food web uptake of selenium. Horn and Roth (1989) found lower levels of selenium in the 20 species of plants and animals studied following flooding with nonseleniferous waters. This decrease in the amount of selenium present in the plant and animal species is attributed to the chemical reduction of dissolved selenium and selenium in suspended particulates, that occurred after flooding (Horne 1991).

While permanent flooding may appear to be an action which will immobilize selenium in the soil and lessen selenium uptake into the food web, as most of the selenium is reduced to insoluble forms, this action also causes some selenium to percolate to greater depths (Alemi 1988; Weres et al. 1989) and possibly enter into the shallow aquifer below. Another drawback to permanent flooding is that the selenium remains in place and can once again become bioavailable by drying and re-wetting the contaminated area (Horne 1991). Because of selenium's unstable chemistry, its distribution and availability are expected to change over time (Tokunaga et al. 1991; Wahl et al. 1994). Wahl et al. (1994) feel that monitoring Kesterson at 2-5 year intervals would provide sufficient time resolution to determine if significant changes in the selenium levels have taken place.

Effects On Aquatic Species And Waterfowl

Numerous studies have investigated the effects of wildlife exposure, direct or indirect, to high concentrations of selenium and the possibility of selenium

bioaccumulation in the food chain. From these studies, investigators have determined the manner and level of selenium up-take that produces adverse effects in aquatic organisms. Standards for selenium exposure have been set based on these investigations.

Waterfowl are exposed to selenium through dermal sorption of the element from contaminated waters and through ingestion of contaminated food. Selenium present in water may be taken up by aquatic organisms, bioaccumulating to high levels and resulting in adverse effects such as sickness, deformity in offspring and reproductive problems in adult animals (Presser and Ohlendorf 1987; U.S. EPA 1987; Benson et al. 1992). Adverse effects begin at concentrations as low as 10 mg/l and death occurs at concentrations of 100 mg/l and above (Heinz et al. 1987). U.S. EPA Ambient Water Quality Criteria for Selenium (1987) states that a 24-hour average of 25 ug/l of inorganic selenite should not be exceeded in areas inhabited by freshwater aquatic life and at no time should the concentration exceed 260 ug/l if the safety of aquatic life is to be maintained. Studies conducted by Bennett et al. (1986) corroborate this finding.

In a laboratory study conducted on Kesterson soils by Poister and Tokunaga (1992), the selenium remediation goal of 2 to 5 ug/l (Wahl et al. 1994) was not attained in the surface waters formed by water table rise. A survey of the ephemeral pools at Kesterson in 1987 found concentrations greater than 1,000 ug/l along with dozens of waterfowl killed by selenium toxicosis (Benson et al. 1992). Poister and Tokunaga (1992) concluded that seleniferous pools formed by water table rise posed a

threat to wildlife.

Selenium may be taken up by ingestion of contaminated food, which results in sickness and reproductive problems in adult animals and deformity in offspring (U.S. EPA 1987). For example, Bennett et al. (1986) found that fathead minnows (*Pimephales promelas*) that were fed food contaminated with selenium weighed significantly less than those fed uncontaminated food. More recently, Skorupa and Ohlendorf (1991) found high embryonic mortality, abnormalities of young, and decreased reproductive success in avian species exposed to contaminated drainage water. While uptake by dermal exposure or ingestion may both produce negative effects, there is controversy as to which is more rapid and more permanent (U.S. EPA 1987).

Selenium concentrations in living organisms increase as selenium bioaccumulates and moves through the food web (Schuler 1987; Bennett et al. 1986; Alemi 1988). This may occur when selenium is in an organic form, contained in vegetation, (Bennett et al. 1986), or when it exists as a solute and is absorbed by vegetation and the vegetation consumed by wildlife (Alemi 1988). Accumulation of selenium within an organism was found to be highest in aquatic plants and microinvertebrates. Terrestrial plants, sediments, and water were also found to accumulate selenium (Ohlendorf et al. 1988; Schuler 1989). Aquatic insects and mosquito fish were both found to accumulate selenium to levels higher than their respective food sources (Bennett et al. 1986; U.S. EPA 1987; Presser and Ohlendorf 1987). Ohlendorf et al.

(1986) concluded that high mortality rates of waterfowl at Kesterson were a result of the high levels of selenium that had entered the food chain. Studies conducted by Ohlendorf (1989) showed similar results. Rabbits at the Kesterson Refuge had concentrations of selenium that were 17 times greater than those in a control area (Benson et al. 1992). Kit foxes, coyotes, raptors, and other predators also run the risk of selenium toxicosis (Benson et al. 1992).

Previous Studies At Kesterson

After the closure and subsequent "dry out" of Kesterson in 1986, ephemeral pools began to form during the wet season. Pools are created by water table rise and rain water ponding. Since filling of most low-lying areas of Kesterson Reservoir with soil in 1988, rain water ponding has become the primary cause of pool formation. Tests conducted on the pre-fill pool waters concluded that selenium concentrations were as high as in the initial drain water (Benson et al. 1992). Due to the dangerously high levels of selenium, several remediation attempts, studies, and monitoring programs have been established. The most pertinent studies are those conducted by Lawrence Berkeley National Laboratory (LBNL) and the United States Bureau of Reclamation (USBR).

LBNL has conducted a variety of ephemeral pool studies. As part of their investigations, Tokunaga and Benson (1992) have determined that excavation of contaminated surface soil is not an effective strategy for decreasing selenium

concentrations in ephemeral pools. This strategy is not effective because there is an adequate supply of selenium at depth to be carried upwards as the shallow water table rises. In addition, LBNL has established an on going monitoring program. The program calls for ephemeral pool waters to be sampled 3-6 times throughout the wet season (approximately December-March), with waters being analyzed for total soluble selenium. This program has revealed many pools that do not meet the wildlife remediation goal of 2-5 ug/l with some samples as high as 1,000 ug/l. Sampling also indicates a seasonal change in pool selenium concentration.

The USBR established its own monitoring program in 1987. Under this program, water samples were gathered from the shallow aquifer below Kesterson and wells in the surrounding area, and in various ephemeral pools at Kesterson. Water samples were tested for a variety of elements including selenium. The ephemeral pool monitoring program has continued on a yearly basis. Some ephemeral pools have been sampled each wet season from 1987 to the present (1997), while other pools were sampled in only 1 or 2 years. The results of each year's sampling are compiled in a USBR report. The report for 1996 shows that only 1 of 15 pools had a selenium concentration below the 2-5 ug/l wildlife safety standard; 14 of the 15 pools exceed this goal at sometime during the wet season (December-March) (USBR 1996).

Summary

Numerous studies have established that selenium bioaccumulates in the food chain and that exposure, direct or indirect, to high concentrations of selenium has negative effects on wildlife. Studies have also shown that as the amount of water soluble soil selenium changes so will the amount of biologically available selenium in the water of ephemeral pools. Statistical analysis of pool selenium concentrations has not yet been conducted on the data collected by the USBR. Results from this analysis will be valuable in improving future sampling schemes, as well as for extrapolating from laboratory investigations in bioaccumulation to model conditions at Kesterson. Year-to-year analysis results will be important in developing future management strategies.

SITE DESCRIPTION

Kesterson Reservoir is located within Kesterson National Wildlife Refuge in Merced County, California, near the town of Gustine (Figure 3). The Reservoir is a 500 hectare expanse of land divided into twelve areas (Figure 4). These twelve areas were used as evaporation ponds for agricultural drain water laden with selenium from the period 1978-1986. Ponds 1 through 6 were managed as year-round wetlands; Ponds 7 through 12 were managed as seasonal wetlands. All twelve ponds originally contained the same general soil type, Turlock sandy loam (Tokunaga pers. com. 1996). In 1988, selected areas of each pond were filled with imported soil, soil from the dikes at Kesterson, and various mixtures of Kesterson and imported soils.

Vegetation types are variable over the 500 hectares and coverage is not uniform. Three habitat types, open, fill, and grassland, have been identified at Kesterson (CH2MHill pers. com.; Tokunaga pers. com.; Wahl et al. 1994) (Figure 5). Open habitats comprise approximately 13 percent of the 500 hectares. These areas contain remnants of cattail tubers (*Typha sp.*), *Bassia*, prickly lettuce (*Lactuca serriola*), and clover (*Medicago, melilotus, trifolium spp.*). Organic detritus in the open habitats contain high amounts of selenium. Grassland (unfilled) habitats comprise 31 percent of Kesterson Reservoir. Currently dominated by saltgrass (*Distichlis spicata*) and annual grasses and forbs, these regions were vegetated with saltgrass (*Distichlis spicata*) and alkali weed (*Cressa truxillensis*). Fill habitats comprise 56 percent of Kesterson Reservoir. These areas are the most difficult to define clearly. Currently,

most fill habitats contain annual grasses and are dominated by *Bassia hyssopifolia*.

Figure 3. Location of Kesterson Reservoir, Merced County, CA.

Figure 4. Illustration of the twelve Kesterson Reservoir evaporation ponds.

Figure 5. Main habitat types found at Kesterson Reservoir.
(Courtesy of CH2MHill, 1996)

Study Sites

Eight areas within Ponds 6, 5, 4, and 2, were chosen as the specific study sites for this project (Figure 6). The choice of the four Ponds was based on several factors. These pond areas have been previously studied by Tokunaga, et al. (1991, 1992) and/or Lawrence Berkeley National Laboratory (LBNL) (1992, 1993, 1994) and/or the USBR (1988-1996) and were found to have seasonal differences in selenium concentrations in ephemeral pool waters. In addition, the USBR restricted access at Kesterson to only Ponds 6, 5, 4, and 2 and accessibility during the rainy season limited pool selection to areas located along Gun Club Road. Of the accessible pools, two pools in each of the four ponds were selected at random for study. Access limitations may have resulted in some bias in the results as pools located near the road might be lower and subject to more flooding, thus decreasing pool selenium concentrations.

This possible bias will not interfere with the goal of determining changes in selenium concentration during the wet season as this newly collected data will not be used in this analysis. The newly collected data will be used, in combination with historical data from 1996, to evaluate current exposure levels at Kesterson. Because the eight new sites might be lower, subject to more flooding, and thus have lower selenium concentrations than other sites at Kesterson, the selenium concentrations obtained at these 8 new sites might not be representative of other pools at Kesterson. This would give a false picture of the present exposure risk. However, data from

other sites at Kesterson will also be used for this evaluation and possible bias will be considered when evaluating the exposure risk.

Figure 6. Location of study sites within Kesterson Reservoir.

The following paragraphs describe each pond:

Pond 2 is located south of Gun Club Road and west of the San Luis Drain. The majority of this pond is of open and fill habitat types. Open areas contain remnants of cattail tubers (*Typha sp.*), *Bassia*, prickly lettuce (*Lactuca serriola*), and clover (*Medicago, melilotus, trifolium spp.*) and organic detritus that is high in selenium. Fill areas have been covered/filled in with imported soil, soil from the dikes at Kesterson, and various mixtures of Kesterson and imported soils. Parts of this pond have been subjected to flooding by rainfall ponding during wet seasons. The highest measured ephemeral pool selenium concentration (1,600 ug/l) in this pond was found in the south east corner of this area (USBR 1996). This site within Pond 2 may also be influenced by an elevated water table (Table 1) (Appendix B).

Pond 5, located north of Gun Club Road and west of the San Luis Drain, is also flooded by rainfall ponding during wet seasons. The majority habitat types are open and fill with some grassland areas. Selenium concentrations in two locations in the western end of the pond were found to be between 83-86 ug/l (USBR 1996) (Table 1) (Appendix B).

Pond 4, located south of Gun Club Road and west of Pond 2, is composed of open and fill habitat types. The selenium concentration in an ephemeral pool located in the northwest corner of the pond was previously measured at 790 ug/l (USBR 1996) (Table 1) (Appendix B).

Pond 6, located north of Gun Club Road and west of Pond 5, was found, by USBR (1996), to have the lowest (17-73 ug/l) ephemeral pool selenium concentration of any of the 4 ponds (Table 1) (Appendix B). It contains open, fill, and grassland areas.

Table 1. Summary of pond habitats and concentrations measured prior to this study (USBR, 1996).

Pond number	Location with respect to Gun Club Road	Habitat type	Highest Se conc found
2	South	open/fill	1,600 ug/l
5	North	open/fill/ grassland	83-86 ug/l
4	South	open/fill/	790 ug/l
6	North	open/fill/ grassland	17-73 ug/l

METHODS

Overview

The objectives of this project are: (1) to examine the spring seasonal (approximately December-March) variation in ephemeral pool selenium concentrations in 1988-1997, (2) to determine if a significant multi-year trend (for the years 1988 through 1996) exists and (3) to determine if current ephemeral pool selenium concentrations meet the wildlife remediation goal of 2-5 ug/l. To fulfill these objectives, selenium data were collected in the field at eight sites in 1996-1997 and these data were combined with results from previous studies conducted by USBR and LBNL.

Existing Data

Monitoring records generated by the United States Bureau of Reclamation (USBR) for the years 1988 through 1996 and records from the Lawrence Berkeley National Laboratory (LBNL) for the years 1992 through 1994 (collected by Dr. Tetsu Tokunaga) were used to assess potential trends in selenium concentration change.

There are a number of shortcomings of the USBR data set for the present purpose. Although several pools in each pond were sampled each wet season, sampling was conducted neither on a regular schedule nor at regular time intervals. Several pools in each pond were chosen for sampling. Some pools were sampled a maximum of six times during the wet season, while others were sampled only one time. However, it appears that many, roughly 60 percent, of the samples were taken

23 to 38 days after each pond formed and very few (roughly 15 percent), were taken during the first six days after each pond formed. This is particularly problematic for tracing year-to-year changes in selenium concentration. Data from this time period are necessary to perform the multi-year analysis. Each year that the USBR monitoring program was in place another group of pools was selected for sampling. Some of the pools in the group had been sampled in the previous year and others had not been previously sampled. This lack of consistent sampling, from year-to-year, does not provide a complete data set for analysis. Water samples were analyzed for total water soluble selenium (Se (IV) and Se(VI)) using hydride generation atomic absorption spectrometry as described in Weres et al. (1989).

LBNL records were generated each year during the wet season in a similar fashion. However, the LBNL monitoring plan was more consistent. Pools were sampled a minimum of three times per season with samples taken at intervals of 15 days or more. At least 80 percent of the LBNL pools were sampled during the first six days after pool formation. The LBNL water samples were also analyzed for total water soluble selenium using hydride generation atomic absorption spectrometry.

New Data Acquisition

New monitoring data were collected for selenium concentrations at eight ephemeral pools during the 1996-1997 season. Two sites, in each of the previously mentioned Ponds (6, 5, 4, and 2), were selected at random for sampling. Sites were selected at

random as previous USBR and LBNL site locations were mapped, but not clearly marked. Without clear field markings, it is difficult to accurately determine pool locations. Sampling began on 28 December 1996 and ended on 28 March 1997. To be consistent with the previous USBR work and/or LBNL studies, a sample was taken from each pool 3-4 times during the season. The final 1-2 sample(s) were taken during the "dry out" phase of the pool. The "dry out" phase occurs when net evaporation exceeds net rainfall and typically begins the middle of February. Samples should be taken during the "dry out" phase to determine exposure levels as pool waters evaporate, possibly increasing the pool selenium concentration. As well, to determine if selenium, previously reduced when flooding conditions were established earlier in the season, is released as pool waters evaporate.

A total of 25 surface water samples were collected from the ephemeral pools. A sample was taken from each of the eight pools every 15 days with the first sample being taken during the first 6 days after pool formation. Sampling continued at 15 day intervals until the pool was dry, for a total of 3 to 4 samples from each pool during the season. Samples were filtered through a 0.45 μ m filter, and transported to a commercial laboratory for same day analysis, as recommended by Tokunaga (Tokunaga pers. com. 1996). To be consistent with USBR and LBNL methods, analysis for total water soluble selenium (Se (IV) and Se (VI)) was conducted using hydride generation atomic absorption spectroscopy, as described in Weres et al. (1989). The analysis was performed by a commercial laboratory (A&L Agricultural

Laboratory, Modesto, California, EC # 1657).

Creation of Data Base

New data were combined with data from historical records to create a data base (Figure 7). Data, on ephemeral pools that had been sampled more than three times during a given wet season, were used to perform the within season analysis, as described below. Data from this data base were also used to attempt the multi-year time frame analysis. However, the data base did not contain sufficient information to conduct this analysis, short comings described below.

Figure 7. Flow chart showing data acquisition, data analysis, conclusions, and implications steps.

Within Season Time Frame Analysis

The question of seasonal dynamics in selenium concentration was addressed using the Lawrence Berkeley National Laboratory (LBNL) data from 1992-1994 and United States Bureau of Reclamation (USBR) data from 1989-1996. New data collected this season were not used in this analysis as accurate electrical conductivity readings were not available. This analysis was looking for a consistent pattern in seasonal selenium concentration dynamics. The dynamics previously observed are due to several factors, including variations in rainfall and water table rise, variations in the amount of surface runoff (containing selenium and other salts), and the binding and release of water soluble/bioavailable selenium.

In order to study the dynamics created by the binding and release of selenium, the data needed to be corrected to reduce those effects created by variations in rainfall and water table rise. This was accomplished by using electrical conductivity data. Selenium concentrations were standardized by dividing by the electrical conductivity (measured in dS/m) taken during each sampling time. This procedure, recommended by Tokunaga (Tokunaga pers. com. 1996), yields a ratio that can then be used to determine if selenium is being removed preferentially over other salts.

In addition, seasonal data vary from year-to-year with respect to date of first ponding for the year. Therefore, to compare data, the date of first ponding also needed to be standardized. Variations in the date of first ponding were standardized by determining when each sample was taken with reference to the date of first

ponding for that particular year. The date of first ponding is determined for the reservoir as a whole by LBNL and/or USBR. This date is the date when heavy precipitation and emergence of the water table are sufficient to cause ponding. The date of first ponding in each year was assigned the number 1, and days were numbered consecutively thereafter to standardize the time periods, some numbers are negative because ponding does not occur on exactly the same date over the entire reservoir. Ideally, all data should be referenced to the day of first ponding for each individual pool. However, this was not possible as these data do not exist.

The sampling season was then divided into eight periods, each 15 days long. Within each period, there were between 5 and 90 data points (Figure 8). The number of points in each period varied as more of the data were collected by the USBR toward the latter part of the wet season (ie. post time period 3, during the "dry out" period). The data in each time period were not normally distributed. To achieve normal distribution, the data were log transformed. Then, the periods were compared using ANOVA to determine differences in selenium concentration over time.

Figure 8. Number of data points in each time period. Data taken from USBR 1989-1996, LBNL 1992-1994, and newly collected 1997 data.

Multi-year Time Frame Analysis

For the multi-year selenium concentration trend analysis, data were standardized by the same methods described for the within season time frame analysis. The within season analysis showed that the selenium concentrations in the ephemeral pools tend to trend systematically over the season with concentrations being highest during the second time period. Ideally, to standardize the between-year comparisons, the 15-day period with the highest mean selenium concentration, the second 15 day time period, should be compared among years. Unfortunately, the data available from the USBR and LBNL were not appropriate for this comparison because many ponds were not sampled in more than one year or more than once during the second, 15-day time period. And, because of the large variation in pool selenium concentrations, both between individual pools and among time periods, it was not possible to extrapolate data with sufficient accuracy for the second time period.

RESULTS

Within Season Dynamics

A total of 25 samples were taken during the 1996-1997 wet season (Appendix A). Selenium concentrations were found to vary among pools and to decrease throughout the season (Figure 9). The highest selenium concentration was found to be 738 ug/l and the lowest 2 ug/l (Table 2).

Table 2. Summary of newly collected data.

Time Period	1	2	3	4	5	6	7	8
Average Se conc	---	---	190	31.3	13.7	14.4	---	---
Variance	---	---	85,625	5,228	332	---	---	---
# of samples	---	---	8	8	8	1	---	---

Figure 9. New data collected on ephemeral pool selenium concentrations during the 1996-1997 wet season.

Selenium concentrations, from samples taken by USBR, LBNL, and 1996-1997 wet season, in the ephemeral pools at Kesterson were found to vary significantly ($p=3.78 \times 10^{-7}$, alpha 0.05) (Table 3) within the December to March sampling period showing a downward trend (Figure 10) (Appendix A).

Table 3. ANOVA single-factor results from the within season concentration analysis.

ANOVA: Single-Factor

Summary

Time Period	Count	Sum	Average	Variance
Interval 1	5	43	8.6	70.3
Interval 2	29	4557.11	157.14	10,6060
Interval 3	80	4978.9	62.24	24,637.4
Interval 4	111	2367.61	21.33	2,672.2
Interval 5	62	1009.3	16.28	543.9
Interval 6	75	1334	17.8	508.5
Interval 7	24	288.11	12.00	141.5
Interval 8	27	364.9	13.51	237.3

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Intervals	584,743	7	83534.7	3.395	3.78E-07	2.0322
Within Intervals	529,049	405	1,3062.9			

Total	5,875,229	412
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Figure 10. This figure illustrates the downward trend of the selenium concentrations in the ephemeral pools.
Data include: new data (1997), USBR(1989-1996), LBNL(1992-1994).

Selenium concentration/ electrical conductivity ratios in the ephemeral pools at Kesterson were found to vary significantly ($p=0.0039 \times 10^{-4}$, alpha 0.05) (Table 4) (Figure 11) within the December to March sampling period. A total of 336 samples were used (Appendix A).

Table 4. ANOVA single-factor results from the within season, selenium concentration/ electrical conductivity ratio, analysis.

ANOVA: Single-Factor

Summary

Time Period	Count	Sum	Average	Variance
Interval 1	5	6.37	1.27	0.430
Interval 2	27	37.2	1.38	0.392
Interval 3	67	65.9	0.982	0.193
Interval 4	90	93.9	1.04	0.599
Interval 5	41	38.5	0.939	0.799
Interval 6	59	42.6	0.723	0.162
Interval 7	23	13.8	0.599	0.098
Interval 8	24	11.7	0.487	0.135

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Intervals	17.2	7	2.45	6.455	3.9E-07	2.04
Within Intervals	125	328	0.380			

Total	141.736	335
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Figure 11. Average $\log(\text{se concentration } \mu\text{g/l} / \text{dS/m} + 1)$ and variance during each time interval. Selenium concentrations are standardized using electroconductivity (EC) in units of dS/m , and normalized using a $\log(x + 1)$ transformation.

The highest average value of 1.37 ug/l / ds/m (log (selenium concentration/EC + 1)) was found within the second time period. The lowest average value, 0.47 ug/l / ds/m, was found within the eighth time period (Table 5).

Table 5. Summary containing minimum, maximum, average selenium concentration ug/l / dS/m, and standard deviation.

Time Period	n	Min Se conc/EC	Max Se conc/EC	Avg Se conc/EC	Standard deviation
1	5	0.53	2.30	1.27	0.66
2	27	0.03	2.61	1.37	0.63
3	67	0.21	2.14	0.98	0.44
4	90	0.02	3.57	1.04	0.77
5	41	0.07	4.00	0.94	0.90
6	59	0.05	1.65	0.72	0.40
7	23	0.12	1.32	0.60	0.31
8	24	0.10	1.44	0.47	0.37

The 8 time periods were then analyzed in pairs to determine where the significant differences lie. Of the 28 comparisons made, 17 produced significant results (Table 6).

Table 6. ANOVA comparison between time periods within a single season.

Time periods compared	p-value	Time periods compared	p-value	Time period	"Days since first ponding"
1&6	0.007*	1&2	0.735	1	-25 to -10
1&7	0.001*	1&3	0.17	2	-9 to 6
1&8	0.001*	1&4	0.515	3	7 to 22
2&3	0.001*	1&5	0.423	4	23 to 38
2&4	0.041*	3&4	0.565	5	39 to 54
2&5	0.030*	3&5	0.735	6	55 to 70
2&6	0.000*	4&5	0.496	7	71 to 86
2&7	0.000*	5&6	0.104	8	87 to 112
2&8	0.000*	5&7	0.083		
3&6	0.001*	6&7	0.19		
3&7	0.000*	7&8	0.267		
3&8	0.000*				
4&6	0.004*				
4&7	0.008*				
4&8	0.001*				
5&8	0.021*				
6&8	0.015*				

* denotes significant p-value ($p < 0.05$)

Selenium concentrations were found to decrease, due to binding and release of selenium, from time period 2 to time period 8. The significant ($p=0.0039 \times 10^{-4}$) downward trend in the pool selenium concentration/ electrical conductivity ratio, and normalized using a log transformation ($\log(x+1)$) is illustrated in Figure 12. This figure depicts what is happening "chemically". The average pool selenium concentration in ug/l during each time period is shown in Figure 13. Concentrations shown in Figure 13 are reflective of the actual concentrations that wildlife are exposed to and may be directly compared to the 2-5 ug/l wildlife safety standard.

Figure 12. This graph illustrates the significant ($p = 3.9 \times 10^{-7}$) downward trend of the average selenium concentration within the season. The average selenium concentration ($\mu\text{g/l}$), divided by the electroconductivity (dS/m), and log transformed ($\log(x + 1)$). The variances are represented by the error bars.

Figure 13. Average pool selenium concentration during each time period grouping. The dotted line represents 5 ug/l.

Of the 95 data points (USBR, LBNL, and new data) collected during the 1996 and 1997 seasons, 72 points (approximately 78%) exceeded the upper level of the wildlife safety standard (5 ug/l) during one or more time periods. The percentage of points that exceed the safety standard varies among time periods, from 56.5% to 100% (Table 7).

Table 7. Minimum, maximum, and average selenium concentration ug/l in each time period. Percentage of data points which exceed the 5 ug/l wildlife safety standard.

Time period	n	Min Se conc	Max Se conc	Avg Se conc	% w/ Se conc > 5 ug/l	% w/ Se conc < 5 ug/l
1	0	0.00	0.00	0.00	0	0
2	15	0.01	1,600	247.73	93	7
3	23	0.01	960	126.54	78	22
4	23	0.01	390	39.32	56.5	43.5
5	15	1.00	130	25.47	80	20
6	16	2.10	150	30.67	75	25
7	2	13	51	32.00	---	---
8	1	14.4	14.4	14.4	---	---

Note: time periods 7 and 8 have insufficient data to make a logical comparison with the other 6 time periods.

Multi-year Trends

From the available LBNL and USBR data, records were found for 32 ephemeral pools that had been sampled in more than 1 successive season. The within season analysis showed that selenium concentrations were highest during the second time period (Figures 12 and 13). The multi-year analysis requires comparing the time period with the highest concentration. Only one pool, of the 32 with more than 1 year of data, fell within this time period. Because of the noise and the large variation in pool selenium concentrations it was not possible to accurately extrapolate data for the second time period to increase the sample size. Therefore, the sample size was not adequate to perform any statistical analysis. For the multi-year analysis to be successful, yearly data collected from the same pools, during the second time period, would be required.

DISCUSSION

The objectives of this study were to assess if and how the levels of selenium in the ephemeral pool waters at Kesterson varied within a season and changed from year to year, as well as to determine the current selenium concentrations to which organisms were being exposed.

Selenium concentrations were found to vary significantly within a single season, with the highest concentrations being around the date of first ponding, diminishing thereafter, periods 2 through 8 (Figures 10 and 11). This finding is consistent with LBNL studies that show a similar trend (Tokunaga and Benson 1992; Zawislanski et al. 1995). Tokunaga and Benson (1992) demonstrated that during the 1987-1988 wet season, the selenium concentrations in the pools studied declined during the first 90 days. This finding supports previous LBNL studies that concluded that initially high concentrations were due to seleniferous waters being carried upward by water table rise and rainwater dissolution of selenium salt crusts on the soil surface (Tokunaga and Benson 1992; Tokunaga et al. 1991). Likewise, studies conducted by Zawislanski et al. (1995) showed the selenium concentration decreased through the beginning of the season. The most plausible explanation for the decrease in selenium concentration is that chemically reducing conditions were established as the pools formed. Reducing conditions would decrease the level of water soluble selenium in the ephemeral pool waters. This explanation is supported by Long et al. (1990), who concluded that flooding may establish reducing conditions in which a lesser amount of soluble

selenium would be available in the water.

Analysis of data from the years 1989-1996 showed that significant decreases in selenium concentration occurred at irregular intervals. For example, a significant change was found after just 15 days, between time periods 2 and 3. But, 45 days were needed to produce the next significant change, between time periods 3 and 6, and 30 days for the significant change between time periods 6 and 8 (Figure 14). The first drop in selenium concentration appears to be the most dramatic. Subsequent drops in concentration do not appear as large. More study is needed to determine whether concentration reduction times tend to fall within a specific time range.

Based on the within season analysis, the second time period, from -9 to 6 days after first ponding, was found to have the highest selenium concentration. This initial, high concentration is due to seleniferous waters that are carried upward by water table rise and rainwater dissolution of selenium salt crusts on the soil surface (Tokunaga and Benson 1992; Tokunaga et al. 1991). This concentration is reflective of conditions before reducing conditions are established in the pools (Long et al. 1990). When conducting a multi-year study of selenium concentrations, data should be collected from this time period to study the maximum exposure level. Though 8 years of data, from 1989-1996, were collected by the USBR, very few, if any, of the yearly samples were taken during the second time period. Of the 32 pools repeatedly examined by the USBR (1989-1996) and LBNL (1992-1994), only one contained data during the second time period. For analysis of multi-year trends, more complete and consistent

monitoring is needed, especially during the critical high exposure period.

Figure 14. Time over which a significant change in selenium concentration was found to occur.

The data collected, by the USBR (1987-1996) and LBNL (1992-1994) may have been collected for purposes other than determining multi-year trends, and therefore, were not collected during the appropriate time period. Existing data have provided a basis for the multi-year study. If the ultimate goal of the USBR monitoring program is to provide sufficient data to be used in completing the multi-year analysis and in developing appropriate management strategies for future use at Kesterson, current monitoring practices will need to make a greater effort to collect data during the critical, high concentration time period. The findings from this study can help future researchers focus sampling for more specific goals.

The wildlife remediation goal of 2-5 ug/l was exceeded in the majority of the pools studies in the 1996 and 1997 seasons. Ninety-three percent of the pools were found to exceed this goal during the second time period. And, at best, only 43.5% of the pools were in compliance during the fourth time period. These findings parallel those of Tokunaga and Benson (1992) and Poister and Tokunaga (1992). Tokunaga and Benson (1992) commonly observed ephemeral pool selenium concentrations of 1,000 ug/l. The Poister and Tokunaga (1992) study, concerned with selenium transport by water table rise, found that the wildlife remediation goal was exceeded in all laboratory tests conducted in their study. When looking at the percentage of pools that exceed the wildlife remediation goal, it is clear that Kesterson Reservoir is still a toxic site for wildlife during the rainy season. In addition, because remediation goals have not been met, it appears that remediation measures to date, such as filling and

excavation, have been unsuccessful in reducing selenium concentrations to acceptable levels.

RECOMMENDATIONS

Systematic patterns within the seasonal selenium concentrations mean that the time and extent of exposure to selenium contaminated waters will vary during the season. It is reasonable to assume that variations in the selenium concentration would effect the rate and level at which selenium bioaccumulates in individual organisms and the food chain. Future field investigations dealing with selenium up-take and bioaccumulation would be most accurate when sampling of pool waters and organisms is carried out multiple times during the season. Investigations and recommendations by wildlife biologists are needed. Multiple sampling periods would provide a clearer picture of exposure and up-take levels in the field than would a single, end-of-season sample. Samples should be taken using the December to March wet season, and analyzed using the same 8 time periods used in this study. Samples taken in this manner may then be compared more easily and accurately. Particular emphasis should be placed on the first through third time periods as this is where the highest concentrations are found, and when the greatest change in concentration occurs. Also important to consider, would be the timing of wildlife "visits" and the timing of biotic processes for those organisms living in the pools at Kesterson

Laboratory studies, meant to mimic field conditions, should vary exposure levels. This variation is necessary if laboratory studies are to be compared with field studies and if laboratory findings are to be used in making accurate field bioaccumulation

calculations.

With regard to the significance of year-to-year trends, no direct conclusions may be drawn because data were not collected during the appropriate time interval. Data not collected during the second time period are not indicative of initial pool conditions as the soluble selenium in the pools is subject to reduction later in the wet season. For a successful, multi-year study, yearly data collected from the same pools, during the second time period, would be required. Future work needs to collect data during each of the eight time periods, with particular emphasis on the second time period. The pools must be monitored continually in successive years. In this manner, a comprehensive, historical record with sufficient data, during the appropriate time period, would be established.

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APPENDIX A

selenium concentratin in ug/l

Data are from this season 1997, USBR 1989-1996, and LBNL 1992-1994.

SITE	Days since first ponding						
	-25to-10	-9 to-6	7 to 22	23 to 38	39 to 54	55 to 70	71 to 86 87 to 112
RWP2A	22			27	43		
				23			
RWP3A				37	100		
RWP3C				14	17		
				11			
RWP4A	9			15			
RWP4B				4	7		
				3			
RWP5A	1			2			
RWP5B	9			18			
RWP10A	2			5			
P9E		4		4			
P9A			2				
			3				
P9J				3			
				4			
P10E			2				
			2	3			
P11D			11	9	42		
				12			
P1I					8	13	
P2C					20	26	
PG3						13	
						18	
P5J						40	
						39	
P6B				4	5		
P6C				6	5	21	
P9N					3		
					2		
P11D				10	15		
P11E					18	36	
P1C						3	1 2
P2C						8	9
P3E						5	7
						9	
P4A						7	3
						6	
P5C2						10	8
P68.....B						3	2
P6C						4	3
IC						3	4 3
8A						7	6
P8C						12	6
P9N						3	5 3
P10C1						5	0.01
P11C						1	

Days since first ponding

-25to-10 -9 to-6 7 to 22 23 to 38 39 to 54 55 to 70 71 to 86 87 to 112

P12G					9		13	12
P1C			11			14		
P1I			70			7	9	
P2C			13			35	26	
P3A			11			8		
P3B			5			3		
P3D			18			18		
P3E			8			6		
P3H			20			22		
P4E			3			4		
P5C2			180			15	15	
P5J			130			24	30	
P6B			10			5		
P6C			4			7		
P8A			16			12		
P8C			4			5		
P11D			3			3	8	
P1-2....S	0.01	0.01	0.01	1				
P1-SW	10	3	2	3				
P2-ESE	1600	960	390	130	150			
P3-NW	460	36	20	13	14			
P3-SW	18	7	8	13				
P3-W	120	10	10	11	24			
P4N	790	150	86	72	62			
P5-2	83	43	42	34	30			
P5-W	86	30	22	26	29			
P6E	73	16	9	20				
P6-NE	17	5	3	4				
P9-E	27	9	5	8				
P9-S	80	30	5	6				
P10GC	310	73	43	31	57	51		
P11-UCR	42	11	9	10	14	13		
P2S1 POOLS MERGED		566	3	41.8				
P2S2		738	210	44.4				
P4S1		8.9	4.7	3.7				
P4S2		4.6	3.9	3.4				
P5S1		26.6	8.3	6.1				
P5S2		157	13.8	2.6	14.4			
P6S1 POOLS MERGED		23.8	2	2.1				
P6S2		2.6	4.7	5.5				
additional LBL data								
1UZ1		378	316	3.4	4.9	7	22.3	
		364	18.1	4.2				
	101.9	45.7	72.7					
1UZ5	0.6	0.6	2.2	4.8	7.9			
		2.3	3.7		4.3			
			4.2		11.5			
		26	18.7	2.2	3.1	4.4	3.7	
		24.3	3				6.2	
			3.6					
	55.2	71						
1SW		0.4	2.2	0.3				
			1.4	Page 2				

Days since first ponding

-25to-10 -9 to-6 7 to 22 23 to 38 39 to 54 55 to 70 71 to 86 87 to 112

			0.9	1.3	0.3	0.9	0.8	
			1.1	0.9				
				1.2				
		1.7						
1H			0.3	0.1				
		0	0.4	0.3	0	1.6	0.8	
			0.1	0.6				
				0.7				
		1						
3SW			11.3	8.6	12.8			
			11.6	14.9	12.8			
				12.8				
				17.3				
		15	3	9.6	9.9	14	19.6	
			10.2	16.1				
				11.6				
		43.2	23.6					
3NNW			13.4	6.5	15.8	25.3		
			11.2	10.4		18.8		
				35.5	8.3	8	7.9	9.8
				11.4				
				10.9				
		237	74.1					
3W			14.5	2.9				
			8.1	4.3	4.9	4.2		
				4.8		4.9		
						0.4		
		125	38	14.7	5.2	3.6	6.8	4.5
			12.5	14.5				
				11.4				
4N			74.8	43.6	53.1	85.1		
				27.1		62.9		
				50.6				
				52.2				
				55	16.4	48	29.6	40.2
				9				69.3
				14.8				
		251	231	60.3				
9BE		0	0.1	0.1				
				0.5				
				0.5				
				1.1				
				1.7				
			13.4	58.1	12.5	6.5	5.5	4.9
			49.7	30.6				5
				32.3				
11UCR		5.5	8.2	9.7				
				9.7				
				15.3				
				21.5				
				27.3				

Days since first ponding								
	-25to-10	-9 to-6	7 to 22	23 to 38	39 to 54	55 to 70	71 to 86	87 to 112
11UCRE			11	7.5	7	8.7	10.1	13
				10.5				33.2
				5				
11UCRW			4.6	8.1	5.4	7.8	9	12.5
			2.3	4.2				26.1
				5.7				

Electroconductivity in dS/m

Data are from the USBR 1989-1996 and LBNL 1992-1994.

Days since first ponding

	-25 to -9	-9-6	7-22	23-38	39-54	55-70	71-86	87-112
SITE								
RWP2A	0.799			2.78	0.01			
				0.01				
RWP3A				0.01	0.01			
RWP3C				0.01	0.01			
				0.01				
RWP4A	0.934			0.01				
RWP4B				1.31	0.01			
				0.01				
RWP5A	0.376			0.01				
RWP5B	0.94			0.01				
RWP10A	0.01			0.01				
P9E		0.01		0.01				
P9A			0.9					
			1.2					
P9J				1				
				1.5				
P10E								
P11D								
P1I								
P2C								
PG3								
P5J								
P6B								
P6C				1.03				
P9N					0.842			
P11D				0.999	1.34			
P11E					4.88			
P1C						0.234	0.378	
P2C						0.81		1.11
P3E						7.7		7.9
						7.3		
P4A						8.2		8.2
						7.6		
P5C2						7.3		7.1
P68.....B						7.7		7.8
P6C						7.2		7.8
P7C						7.1	7.7	8.2

-25 to -10 -7 to 6 7 to 22 23 to 37 39-54 55 to 70 71 to 86 87-112

P8A						7.7		6.7
P8C						1.08		1.14
P9N						0.905	1.61	1.91
P10C1						0.206	0.01	
P11C						0.766		
P12G					0.638		1.07	
P1C			1.46			3.77		
P1I			3.49			1.315	3.14	
P2C			0.54			1.025	3.38	
P3A			1.84			0.94		
P3B			0.79			0.636		
P3D			1.28			2.42		
P3E			1.06			0.786		
P3H			1.39			1.417		
P4E			0.57			0.932		
P5C2			3.2			2.86	8.4	
P5J			1.88			0.959	2.73	
P6B			0.92			0.683		
P6C			0.85			0.976		
P8A			1.48			0.734		
P8C			0.49			0.356		
P11D			0.49			0.67	2.33	
P1-2....S	0.16	0.2	0.27	0.375				
P1-SW	0.67	0.48	0.577	0.73				
P2-ESE	12.9	8.69	8.7	12.67	14.37			
P3-NW	6.59	4.26	4.16	5.54	6.16			
P3-SW	1.9	2.07	2.74	4.58				
P3-W	4.46	2.06	2.51	3.53	4.03			
P4N	1.96	2.43	2.3	3.71	3.66			
P5-2	1.33	2.7	2.87	3.73	3.97			
P5-W	1.73	2.1	2.52	3.85	3.68			
P6E	2.84	3.84	4.86	9.79				
P6-NE	1.2	1.25	1.255	21.8				
P9-E	3.77	4.08	4.7	10.5				
P9-S	3.51	2.25	2.25	3.39				
P10GC	14.7	15.6	15.93	22.11	29.02	40.48		
P11-UCR	20.2	19.4	20.64	25.23	27.11	41.41		
P2S1 POOLS MERGED								
P2S2								
P4S1								
P4S2								
P5S1								
P5S2								
P6S1 POOLS MERGED								
P6S2								
additional LBL data								
1UZ1		9.8	14.8	0.5	1.8	2.4	3	
		14.1	1.9	1.2				

	-25 to -10	-9 to 6	7 to 22	23 to 38	39 to 54	55 to 70	71 to 86	87 to 112
	5.5	5.3	17.5					
1UZ5	0.1	0.2	0.4	1.4	2.5			
		0.3	1		2.7			
			1		2.9			
		0.8	1.3	0.6	0.8	1	1.6	
		1.1	0.4				2.6	
			0.5					
	1	2.7						
1SW		0.3	0.5	0.6				
			0.7					
		0.2	0.4	0.3	0.5	0.5		
		0.4	0.2					
			0.3					
	0.2							
1H		0.2	0.3					
	0.1	0.1	0.3	0.3	0.7	0.3		
		0.2	0.2					
			0.2					
	0.2							
3SW		1.6	2.5	3.8				
		2.4	3.3	4.2				
			4					
			4					
	1.3	1.2	2.2	1.9	3.3	2.9		
		1.6	1					
			1.7					
	1.4	2.5						
3NNW		1	1.6	2.6	3.7			
		1.4	2.2		4			
			3.1	1.8	2.7	3	4.1	
			1.2					
			1.7					
	3.7	3.9						
3W		1.2	1.3					
		1.3	1.6	1.9	3			
			1.8		3.2			
					3.4			
	3.2	2.5	3.7	1.3	1.6	1.7	2.8	
		2.5	1					
			1.6					
4N		2	1.6	2	2.5			
			1.9		2.8			
			1.8					
			2.2					
			0.8	1.4	1.1	1.5	2.1	
			0.5				2.6	
			1.1					
	1.6	1.7	3.3					

-25 to -10 -9 to 6 7 to 22 23 to 38 39 to 54 55 to 70 71 to 86 87-112

9BE		0.1	0.1	0.2				
				0.4				
			0.6	3.1	2.2	2	3.6	4
			1.9	1.9				4.6
				3.1				
11UCR		5.5	4	4.1				
				4.3				
				5.4				
				6.7				
				7.7				
11UCRE			1.3	2.4	7.8	12.2	13.1	17.9
				2.2				40.5
				3.6				
11UCRW			0.7	3	5.4	11.2	11.6	16.6
				1.6				33.6
				3.5				

APPENDIX B

Photograph of Pond 5, site 2.

Photograph of Pond 4, site 1.

Photograph of Pond 6, site 2.