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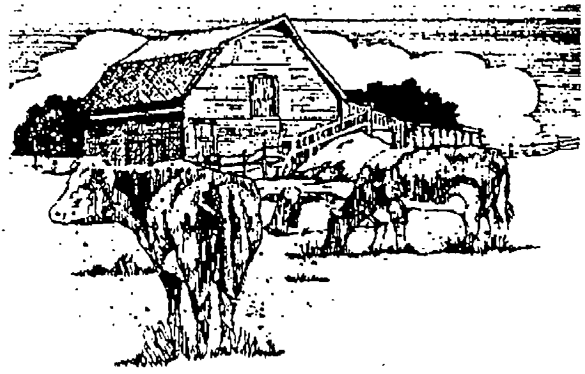

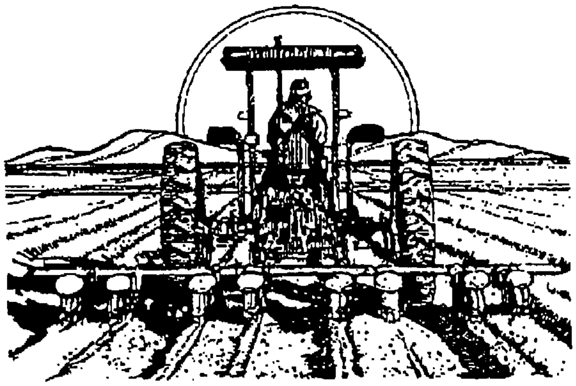

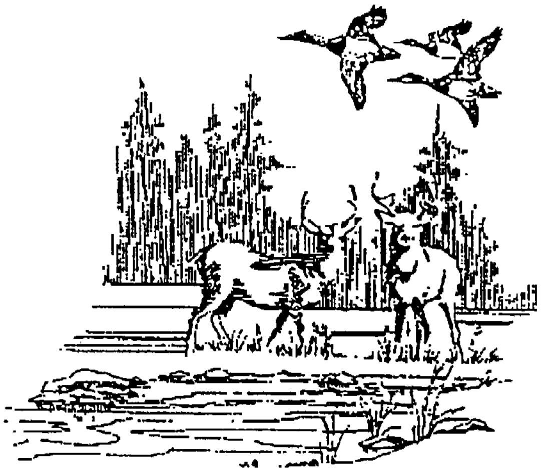

SELENIUM IN CALIFORNIA
VOLUME 2
CRITICAL ISSUES

90-9-WQ

October 1990

WATER RESOURCES CONTROL BOARD
STATE OF CALIFORNIA

SELENIUM IN CALIFORNIA
Volume 2

Critical Issues

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for the
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State of California

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The organizers of the various selenuim conferences and programs over the last few years, and the editors of the conference proceedings, also deserve special credit for their work. This work is rarely acknowledged and poorly rewarded within the academic system, yet is one of the most important techniques for improving integration and interdisciplinary cooperation on this type of complex environmental problem.

A final debt is owed to the many scientists, often unrecognized, whose research has provided the basic information that is included in this report.

SELENIUM IN CALIFORNIA
Volume 2
Critical Issues

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Executive Summary

In 1985, the California Legislature approved a State Water Resources Control Board (State Board) study plan entitled "Selenium and Other Trace Elements in California". The Study Plan called for conducting investigations to find solutions to selenium and agricultural drainage-related problems in California. As a part of the Study Plan, the University of California, Riverside, entered into an agreement with the State Board to prepare a two-volume report addressing selenium issues in California.

Volume 1 (published in 1989) focused on physical, chemical, and biological properties of selenium and provided an overview document on selenium for researchers and regulators. Volume 2 focuses on the issues most critical for California. Chapter 1 is the introduction to Volume 2. Selenium and its relation to irrigated agriculture is briefly presented in Chapter 2. The interrelationship between selenium and human health is given in Chapter 3. The adverse effects of selenium on aquatic and wetland ecosystems is discussed in Chapter 4. The problems of selenium deficiency and toxicity are described in Chapter 5, and methods to minimize the selenium adverse effects are presented in Chapter 6.

Selenium occurs naturally in the environment and occasionally causes deficiency and toxicity problems in wildlife and livestock. Adequate selenium in the diet provides protection against various types of cancer and other diseases. Selenium deficiency is widespread in livestock in California.

Selenium has been found in the soils of the west side of the San Joaquin Valley, west and east sides of the Imperial Valley, and areas of the Colorado River Valley. However, very few plants with selenium levels high enough to be of concern for animals and people have been reported in California. Elevated levels of selenium have been found in fish, game, food, and water. Even these higher levels are considered to be safe by most investigators as a part of normal diet. Department of Health Services has stated that selenium exposure poses little or no threat to human residents in California.

A combination of management and treatment strategies are needed to reduce selenium adverse impacts in California. Source reduction is suggested to be the interim method of reducing selenium problems in wetland and aquatic ecosystems. Selenium volatilization and harvesting appear to be promising techniques for the treatment of agricultural drainage waters.

Conclusions

1. Currently, there are three options to deal with selenium tainted drainage water when it cannot be discharged to surface waters. The options are a rising water table, reuse, and discharge to evaporation ponds. None of these options are particularly desirable. A rising water table would eventually take land out of production. The long-term impact of reuse on

crop production and crop quality is not known. And evaporation ponds pose liability problems as a result of trace element contamination.

There are a number of options for treating agricultural drainage waters to remove selenium. Chemical treatments are not economically feasible for agriculture. The biological treatments are likely to be more economically feasible but remain unproven.

2. Improving irrigation efficiency is considered the first step in reducing the volume of drainage water. Solutions to the problems of selenium-tainted agricultural drainage waters and its adverse impacts requires measures which include:

   (a) providing education to water users and water managers; (b) providing financial incentives for water conservation and drainage reduction rather than for treatment of drainage water; (c) consideration of the net benefit to society of alternatives such as agroforestry, dryland grain, and recreational hunting and fishing; (d) inclusion of selenium control and ground water management in the Conservation Reserve Program; and (e) development of more open water trading and marketing enabling conserved water to be sold.

Technical Summary

1. Selenium is both an essential element and a potential toxicant to human health. Selenium deficiency in humans has been observed throughout the world. Selenium deficiency also affects the immune system and may cause susceptibility to infection and disease. There is information in the literature on the effect of selenium deficiency on skin cancer and breast cancer in women. For example, blood selenium levels of healthy women in Japan and California was significantly higher than women with breast cancer. There are indication to suggest that selenium also plays a role in the treatment and prevention of several other diseases including Aquired Immune Deficiency Syndrome (AIDS). Selenium deficiency in infants due to low selenium levels in women during pregnancy and low selenium level in infant food has been observed. Based on limited information, selenium deficiency has been suggested as an agent in the sudden unexpected death of infants known as Sudden Infant Death Syndrome (SIDS).

2. The average range of the U.S. daily diet intake of selenium is 60-176 micrograms/day versus the National Research Council recommended diet intake of 50-200 micrograms/day. The U.S. Environmental Protection Agency's acceptable daily intake is 210 micrograms/day. The minimum selenium requirement is reported to be 90 micrograms/day. A maximum recommended long-term selenium intake of 775 micrograms/day and a maximum tolerable level of 1000-1500 micrograms/day have been reported by researchers. Levels of up to 1000 micrograms/day probably offer little risk if limited to days and weeks. Proteins, yeast, methionine, and inorganic sulfur compounds have shown varying degrees of protection against selenium toxicity. Adverse effects to humans can occur when selenium intake over long-term is less than 10 or greater than 10,000 micrograms/day.

3. Selenium in agricultural drainage water from the west San Joaquin Valley of California is a major environmental concern. Elevated levels of selenium were measured in broccoli, carrots, cauliflower, garlic, and lima beans grown in the west side of the San Joaquin Valley. However, the average daily intake of selenium from consumption of these and other food crops from the area in a typical diet is expected to be 1-20 microgram/day.

4. Selenium toxicity in wetlands have been observed in California. The bioconcentration (increase of selenium concentration in living organisms) and biomagnification (the rapid increase in concentration through successive steps in the food chain) can cause problems even when ambient selenium levels are relatively low. Elevated levels of selenium and adverse selenium impacts on the fish and wetland birds have been observed in California. Health advisory notices for limited consumption of fish and wildlife from Salton Sea, Grasslands, Kesterson, and Suisun Bay have been issued in the past. Even through no adverse human health

impact from selenium has been observed in California, long term exposure to diet containing other trace amounts of selenium is a human health concern. Pregnant women, children, individuals who consume whole fish, and individuals on diets that increase susceptibility to selenium toxicity (i.e. low protein diets) are at greater risk when consuming fish with elevated levels of selenium.

5. Selenium deficiency is most likely to occur around the western slopes of the Sierra Nevada Mountains and areas in Northern California. Individuals consuming a diet composed primarily of processed food with little whole grain, broccoli, garlic, mushrooms, brazil nuts, oysters, or other seafood and organ meats, such as liver and kidneys, would be most likely to be selenium deficient. Both alcohol consumption and smoking have been linked to reduced selenium levels.

6. Tissue concentrations of a few to tens of thousands times greater than the selenium concentration in water as a result of biomagnification has been observed. While elevated levels of selenium in birds nesting in wetlands with high selenium were noted in California, relatively little is known about deficiency and excess selenium in wild birds, and rare and endangered species. Reproductive impairment relative to birds as a result of elevated selenium in the diet has been observed. Studies with birds suggest that embryotoxic and teratogenic problems become apparent at dietary levels of 7 ppm (dry weight) of selenium. Studies of chickens have shown that chronic toxicity can occur when selenium dietary levels are 7-8 ppm (dry weight).

7. Selenium behavior in the aquatic ecosystems is similar to that in wetlands. Selenium in water or diet can lead to pathological symptoms, reproductive failures, and death in fish. Selenium in fish sampled nationwide averaged 2 ppm (dry weight). The range within California fish varies from less than 1 ppm to more than 430 ppm (dry weight) but is generally within the acceptable limits in game fish. Selenium toxicity in fish is affected by many factors including age, life stage, sex, nutritional status, health, form of exposure, concentration, duration of exposure, and water conditions such as hardness, temperature, and suspended solids. Laboratory studies indicate that selenium levels as low as 6.5 ppm (dry weight) in food reduced survival and growth of chinook salmon.

   The adverse effects of excessive selenium in diets of domestic animals and birds have been well documented in the north central United States. Blind staggers and alkali disease in animals are due to high selenium content in the feed.

Chapter I. An Introduction to Volume 2

A. Introduction

Our purpose in preparing this volume has been to assemble a detailed review of the critical issues involving selenium in California. It follows Volume 1 which was intended to provide an overview document on selenium for decision-makers, managers, and researchers who are working on projects that may involve selenium in California.

In Volume 1 we attempted to summarize the uses, behavior, benefits and problems associated with selenium. In Volume 2 we have concentrated on the issues that appeared most critical for California. These include a more complete discussion of the interrelationship between selenium and human health (Chapter 3); the adverse effects of selenium on aquatic and wetland ecosystems (Chapter 4); the problems of selenium deficiency and toxicity in livestock and wildlife (Chapter 5); and management and treatment options to minimize selenium releases and reduce adverse impacts (Chapter 6). The enormous scope of this project has forced us to make many decisions to limit coverage.

B. Selenium as an essential nutrient

Selenium plays an important role in biology, especially in animal nutrition. Selenium occurs naturally in the environment in amounts which occasionally cause nutritional deficiency or toxicity problems in livestock and wildlife and even more rarely in humans. It is distinguished from most other biologically active elements by the narrow range between deficient and toxic concentrations (see Chapters 3 and 5, and Volume 1, Chapter 3).

The benefits of selenium for nutrition and health were not discovered until the late 1950s. Selenium's essential role in animal and human nutrition was established in more detail in the 1960s. Subsequent research has revealed more about the biochemical roles selenium plays and the importance of selenium for animal and human health, but the complex, interactive roles selenium plays in health and disease has frustrated scientists' attempts to completely understand its function (see Chapter 3).

Subclinical selenium malnutrition and attendant health risks are poorly understood, yet are more likely to occur than acute effects. Adequate selenium in the diet apparently provides protection against various types of cancer and other diseases. Clinical selenium deficiency diseases are probably very rare in California residents, but might occur among homesteaders who rely on home-grown food and fish and game in the selenium-deficient areas of California, or among individuals in special at-risk categories, including premature infants and individuals on total parenteral nutrition.

Selenium supplements for humans are now used in several areas of the world. Selenium supplements have been recommended by several authorities in the U.S., but consensus about the selenium requirement for optimal health is still lacking. More details on selenium and human health are included in Chapter 3 of this report.
Selenium deficiency is widespread among livestock in California and recent studies suggest that it may be responsible for the decline in deer populations in some areas. The widespread occurrence of selenium deficiency in livestock and the growing body of evidence concerning the detrimental effects of selenium deficiency on human immune system response suggests that too-little selenium is as likely to be a problem as excesses. Additional research is needed to confirm these findings and identify other areas where selenium deficiency may be a problem.

C. Selenium excess and selenium toxicity

Excessive selenium, involving soils that are naturally high in selenium, has received the most publicity in California. Selenium is most likely to be abundant in soils derived from the weathering of sedimentary rocks, particularly marine pyritic shales. Seleniferous soils are widely distributed in western North America, particularly in arid and semi-arid areas where the parent rock is Cretaceous or Tertiary marine shale. In these areas, the soils, or occasionally the incompletely weathered parent rock, may support vegetation that has concentrated sufficient selenium to be hazardous for grazing animals. Soil selenium content is generally low in California with widespread areas of selenium deficiency. This explains the limited areas of selenium toxicity in California, as contrasted with South Dakota, North Dakota, Montana, Utah, Wyoming, Nebraska, Colorado, and New Mexico where it is more widespread.

Selenium is rarely if ever taken up by plants at levels high enough to cause injury to plants under natural conditions. Very few plants with selenium levels high enough to be of concern for animals and people have been detected. Although researchers have found elevated selenium levels in some fish, game, food, and water, surveys have uncovered few commodities with elevated selenium levels in the normal food production and distribution system. Even these higher levels are considered to be safe by most investigators as part of a normal diet (see Chapter 3) and the State Department of Health Services has stated that selenium exposure poses little or no risk to the residents of California. Limited consumption of wildlife, fish, and waterfowl from seleniferous areas has been recommended because high selenium levels have been detected in some cases. Some investigators feel that occasional consumption at these higher levels is safe, but chronic consumption of these foods could lead to selenium toxicosis. Further monitoring of these foods and studies of the people who have eaten them for many years are warranted.

People in selenium-deficient areas may benefit from consumption of California foods with slightly higher than average selenium levels.

D. Selenium in agricultural drainage water: An environmental concern in some areas

Trace elements, such as selenium, are found in the soil parent material and consequently in the agricultural drainage waters of the west side of the San Joaquin Valley, the west and east sides of the Imperial Valley, and potentially other areas including the Colorado River Valley (Chapter 2). Selenium does not affect the crops or potential consumers of these crops; but, wildlife and fisheries can be adversely affected by high selenium concentrations in agricultural drainage water. These impacts can occur on-farm and off-farm in wetlands and river systems (Chapter 4).

E. An integrated approach to solving selenium problems in California

Source reduction is likely to be the most cost-effective method of reducing problems with selenium in wetlands and aquatic ecosystems. Selenium release can be controlled by improving irrigation and drainage practices and cropping systems (Chapter 2, 6). Selenium volatilization and selenium harvesting also appear to offer some potential for the treatment of areas with elevated selenium levels (Chapter 6). A combination of management and treatment strategies may be needed to satisfy the many environmental, economic, wildlife, and human health concerns that resource managers currently face.

Chapter II. Selenium and Irrigated Agriculture

Reports by a University of California Committee of Consultants and the Agricultural Water Management subcommittee of the San Joaquin Valley Drainage Project concluded that the proposed reduction of drainage flows (to meet the interim selenium water quality objective in the San Joaquin River) was feasible... Actual drainage flow reduction will only be achieved after farmers adopt the proposed management practices.

Letey, Dinar, and Knapp 1988

A. Introduction

Selenium is a trace element which occurs naturally in the environment in amounts which have caused both nutritional deficiency (Chapter 3 and 5) and more rarely, toxicity problems in wildlife, fish and birds (Chapter 4). It is distinguished from other elements by the narrow range between sufficiency and excess (see also Volume 1, Chapter 1, 3, and 5). In areas where seleniferous soils occur naturally agricultural operations are responsible for most of the release of selenium into the water and the resulting selenium toxicity problems in wetlands and aquatic ecosystems (see Chapter 4). More commonly, livestock operations suffer from selenium deficiency problems as a result of low levels of selenium in the soil or low selenium availability from the choice of crops and management practices of crops, pasture, range and livestock (Chapter 5).

Selenium toxicity from agricultural drainage water has been observed in wetlands and aquatic systems in the Central Valley of California (Ohlendorf, 1985; Saiki, 1985; Ohlendorf, et al., 1986 a,b,c). Adverse impacts on fish and wetland birds have been the primary problems. Possible impacts on rare and endangered species are also of concern. Bioconcentration (by individual organisms) and biomagnification (the pronounced increase in concentration through successive steps in the food chain) can cause problems even when ambient selenium levels are relatively low. Biomagnification of selenium in the food chain lead to tissue concentrations that are a few hundred to tens of thousands of times higher than the water concentration (Lemly, 1985; White et al., 1988). As a result, selenium concentrations in agricultural drainage water need to be kept at very low levels to avoid harmful effects in wetland and aquatic ecosystems.

Selenium is not applied to the fields but is leached from the soil during irrigation and transferred to the drainage water. The adverse effects of selenium in drainage water are exacerbated when this drainage water reaches seasonal wetlands, where the fluctuation in soil conditions over the year can increase selenium concentrations in the food chain.

The concern with selenium is a small part of a much larger suite of problems related to irrigated agriculture in arid regions, including salinization, rising water tables, and the maintenance of agricultural productivity. These problems are serious in California, where more than one fourth of the irrigated land in the San Joaquin Valley is now affected. In other irrigated areas, such as the Imperial Valley, virtually all of the land under irrigation is affected by high water tables (Backlund and Hoppes, 1984). The annual cost of water-logging and increased salinity for just one irrigation district (260,000 acres) was estimated to be $17 million dollars (Hanson, 1984).

Subsurface drains have been the traditional solution for high water tables and increasing salinity. These costly drainage systems remove excess water, salt, and trace elements, such as selenium from the farmer's fields. Unfortunately, this transfer has adversely affected some wetlands and rivers where the drains discharge (see Chapter 4). Disposing of agricultural drainage water has become increasingly difficult as environmental protection laws have been strengthened (Letey, et al., 1986). Dealing with existing selenium concerns, maintaining agricultural production, and reclaiming lands with high water tables and excessive salinity are among the most serious problems now facing irrigated agriculture in California.

B. The selenium cycle

The main natural sources of selenium in the environment are volcanic action and weathering of marine sediments. Losses of available selenium in an ecosystem occur through the transformation of compounds to elemental selenium and formation of insoluble metal selenides (Weiss, et al., 1971). Living organisms are also able to change inorganic forms of selenium to unavailable elemental forms (Falcone and Dickenson, 1963). Several bacteria and fungi can oxidize colloidial selenium to selenate or selenite (Lipman and Waksman, 1923) and produce methylated selenium compounds that are more available to plants and animals (Barker and Fleming, 1974). These microbial, plant, and animal transformations of selenium compounds appear to be of paramount importance in the cycling of selenium.

Shrift (1964) and Swaine (1978) have described the cycle of selenium in the environment. Allaway (1968) has characterized low, moderate, and high selenium ecosystems in terms of the effects on plants and animals living there (Table 2.1).

Various plant and microbial species methylate selenium (Challenger, 1935; McConnell and Portman, 1952). Abu-Erreish, et al. (1968) suggested that fungal activity is a primary means of selenium volatilization. Barker and Fleming (1974) found several strains of fungi (including strains of *Penicillium* and *Fusarium*) that were capable of producing dimethylselenide (see also Volume 1, Chapter 3). Bacterial methylation of selenium also occurs (Shrift, 1964). Oxidation of elemental selenium to selenite by *Bacillus megaterium* has also been reported (Sarathcandra and Watkinson, 1981).

Higher plants also volatilize selenium. This is most pronounced in the selenium accumulator plants. Some *Astragalus* spp., for example, evolve dimethyldiselenide in amounts proportional to their total selenium content (see Chapter 6). As much as 60% of the selenium in these plants, which can accumulate selenium concentrations of thousands of μg/g dry tissue,

Table 2.1. Generalized characteristics of low, moderate, and high selenium ecosystems.

	Low selenium	Moderate selenium	High selenium
Type of rocks	Varied-igneous	Varied	Sedimentary materials common
Type of soils	Acid, some alkaline	Acid to alkaline	Alkaline
Total Se content of soil	<0.04 μg/g	0.05 - 5.0 μg/g	1-100 ≤ μg/g
Available form of Se in soils	Selenites	Selenites(insoluble)	Selenates and organic Se
Concentration of Se in soil solution	0.001 μg/g	0.01 μg/g	1 μg/g
Forms of Se in plants	Protein bound seleno-methionine	Protein bound seleno-methionine	Soluble seleno-amino accumulators. Protein bound seleno-methionine
Se concentration	<0.04 μg/g	0.1-1 μg/g	1-10 μg/g in food and feed plants. More than 50 μg/g in Se accumulator plants
Se status of animals symptoms	Deficiency disease	no deficiencies, no toxicities	Toxicity

Source: Allaway, 1969.

may be volatilized (Beath, et al., 1937). The amount of selenium volatilized by these accumulator plants can be substantial.

The lifetime of the volatile selenium in the atmosphere is unknown, but there is evidence that other plants may uptake these volatile products. Peterson, et al. (1981) stated that volatile organoselenium compounds released from plants can be reabsorbed from the air into surrounding soil, the type of soil affecting this process. Plants are also apparently able to absorb volatile selenium released from adjacent selenium-containing plants (Asher, et al., 1967). The significance of volatilization in selenium cycling is not well known but it is possibly important where soils containing low and high concentrations of selenium are in close proximity to one another. Although the selenium concentrations of non-accumulator plants may increase from this available selenium, it is also possible for an overall loss of volatile selenium into the atmosphere to occur.

Jernelov and Martin (1975) studied losses of selenium from animals. Ruminant animals are able to reduce dietary selenium to elemental selenium which is excreted in the feces in forms that are unavailable to plants (Butler and Peterson, 1963). Kovalskiy and Andryanova (1968) found that isolates of bacteria, fungi, and actinomycetes from soils containing high selenium contained as much as 0.18% selenium (dry weight) inside their cells. Their resistance to the high selenium levels apparently depends on their ability to reduce the soil-selenium to the biologically inert elemental form.

Selenium is oxidized and reduced through natural processes. The quantitative significance of these processes remain unclear. Organoselenium compounds appear to be the most important mobile phase of selenium in selenium-cycling in natural ecosystems. Volatile organic selenium evolved from soils, plants, and animals in agricultural systems is lost to the atmosphere. Inputs of selenium, largely as inorganic forms, from fertilizers, rain, snow, dust and weathering of rocks may not counterbalance this loss in terms of biological availability.

Animals grazing on areas deficient in selenium can metabolize ingested selenium to the elemental form, which may be rendered unavailable for long periods of time and contribute to the overall deficiency problems. In addition, animals exhale selenium gases which may be lost to the atmosphere. Controlled burning and wildfires can also volatilize selenium and remove it from an ecosystem. The removal of animals and vegetation can transfer selenium out of an ecosystem. Changes in plant communities may also make selenium more or less available. And finally, irrigation water can mobilize soluble selenium in the soil, leading to potential disposal problems or risks of adverse environmental impacts.

C. Selenium in the soil-plant system

1. Soil relationships

Selenium is widely distributed in soils. Usually its concentration is low, approximately 200 to 400 µg/kg in an average soil worldwide (Wiggett and Alfors, 1986). Some soils have selenium concentrations so low that cattle that forage from those rangelands must be given selenium supplements. These low selenium soils may contain as little as 100 µg/kg selenium. In California these soils occur on the eastern side of the San Joaquin Valley, where they are derived from the weathering of low-selenium metamorphic and igneous rocks in the Sierra Nevada and in many areas of Northern California.

Total selenium concentrations in soil parent material were shown to influence selenium concentrations in wheat plants (Doyle and Fletcher, 1977). Parent material maps could form a suitable base for designing plant-sampling programs to outline areas where selenium toxicity and deficiency may occur. Areas that are naturally selenium toxic or deficient have been mapped by determining plant selenium concentrations (Kubota et al., 1967). Seleniferous soils can usually be identified by the presence of selenium accumulator plants. These selenium-indicator plants have also been used to locate new ore deposits (Rosenfeld and Beath, 1964).

Lakin and Davidson (1967), Allaway (1968), and Paasikallio (1981) have extensively reviewed selenium behavior in soil and have emphasized its complex character. In general, in acid gley soils, and soils with high organic matter content, selenides and selenium-sulfides dominate. These are only slightly mobile and not readily available to plants.

In well-drained mineral soils with pH close to neutral, essentially all selenium should occur as selenites. Alkaline metal compounds are soluble, but iron selenites are not; moreover, selenites are rapidly and nearly completely fixed by iron hydroxides and oxides and thus are only very slightly available to plants. And in alkaline and well-oxidized soil selenates are likely to occur. These are readily soluble, are unlikely to be fixed by iron oxides, and may be highly mobile and readily absorbed by plants. However, complex anions of selenium as well as organic chelates greatly modify the behavior of selenium in each particular soil. This has been illustrated by various trends in selenium distribution along soil profiles (Wells, 1967). Table 2.2 presents some of the soil characteristics affecting selenium availability.

Selenium in organic compounds occurs in varying quantities in soils and may result from the decay of seleniferous plants (Beath, et al., 1935). Organic selenium is subject to microbiological breakdown, resulting in the liberation of gaseous alkyl-selenium compounds.

Adsorption of selenite or selenate onto soil materials has been described by the Langmuir adsorption isotherm (Singh, et al., 1981; Rajan and Watkinson, 1976). Several studies have demonstrated that selenite is sorbed on soil to a much greater extent than selenate (Gissel-Nielsen, et al., 1984) and is not as available for plant uptake. However, Singh, et al. (1981) found selenate was sorbed by soils more than selenite and that for both forms of selenium the sorption decreased in the following order: high organic matter soil>calcareous soil>normal soil>saline soil>alkali soil. They found that certain soil properties, such as organic C, clay content, $CaCO_3$ and cation exchange capacity, were related to sorption capacity for selenium. Similarly, John, et al. (1976) found that specific surface area, organic C, free forms of SiO_2, Al_2O_3, Fe_2O_3 and allophane content were closely related to selenium adsorption by soils.

The effect of organic matter on selenium availability is somewhat inconsistent. This is perhaps related to the complex role organic matter plays in the soil environment. Selenium is associated with the organic matter in soils via the cycling of the element through decay of plant material. Therefore, selenium levels in the surface soil layers can be expected to be higher than in the subsoils due to higher organic matter

Table 2.2. Soil characteristics affecting selenium availability[a]

Low availability	Factor	Highly available
low (acid)[b]	*pH*	*high (alkaline)*
low (anoxic)	oxygen	high (oxic)
low	*soil biological activity*	*high*
high	*soil moisture*	*low*
high	clay content	low
high	calcium	low
high	*organic matter*	*low*
high	sulfur	low
high	iron	low
high	aluminum	low
low	phosphorous	high

[a] These relations are generally true but interactions occur and sometimes opposite results are observed.

[b] Italicized items are those most directly influenced by agricultural operations.

content in the former (Levesque, 1974a). Levesque (1972, 1974b) suggested that the selenium was bound to organometallic complexes. These findings, however, are not consistent with plant uptake studies, indicating that more research is needed in this area. Data on Table 2.3 suggests that selenium in toxic soils has mainly concentrated in organic horizons.

2. Plant uptake--crops, consumers, and livestock
The accumulator plants may require selenium for normal growth (Shrift, 1969; Johnson, 1975), but no beneficial effects were reported in agronomic species when selenium was added to purified cultures in which plants were grown (Broyer, et al., 1966). The accumulator plants are able to tolerate thousands of micrograms of selenium per gram of tissue (dry weight) without showing toxicity symptoms. Toxicity of selenium to plants growing under natural conditions has rarely been reported (Hemphill, 1972; NRC, 1976), although non-selenium accumulator plants growing in seleniferous areas may develop

Table 2.3. Variations in selenium and organic matter with soil depth

Soil depth	Selenium	Organic C
cm	µg/g	percent
0-15	20.0	15.5
15-30	175.0	37.5
30-50	6.4	3.3
50-60	100.0	31.3
60-86	2.7	4.0
>86	1.1	0.6

Source: Fleming, et al., 1975.

bleached foliage and stunted growth (Stadtman, 1974). Symptoms of toxicity to crop plants in culture solution have been observed (Fiskesjo, 1979; Singh, 1982).

Surveys of selenium concentrations in crops show that areas producing crops with selenium contents too low to meet animal requirements are more common than areas producing toxic levels of selenium (Gissel-Nielsen, et al., 1984). Plants that are poor selenium-accumulators are particularly likely to result in selenium deficiency in livestock and wildlife (see Chapter 5). Livestock and wildlife consuming plants which contain excessive amounts of selenium can be afflicted with two maladies, commonly known as "alkali disease" and "blind staggers" (see Chapter 5).

There is a positive linear correlation between selenium in plant tissues and selenium content of soils. Sippola (1979) found that total soil selenium gave a better measure of plant response than did the soluble selenium fraction. Soil selenium uptake by plants depends on climatic conditions, water regime of soil, oxidation-redox potential, pH, and sesquioxide content of the soil (Sippola, 1979; More and Coppnet, 1980).

The uptake of selenium by plants is temperature-dependent. Plants absorb more selenium when the air temperature is >20°C than during cooler seasons <15°C (Lindberg and Lannek, 1970). Rainfall may also influence the selenium concentration of herbage. Rueter (1975) found that low selenium concentrations in plants frequently occurred in high rainfall areas.

Cruciferae species contained higher amounts of selenium on a range of soils compared with other plants (Hamilton and Beath, 1964). Bisbjerg and Gissell-Nielsen (1969) found the following decreasing plant selenium concentrations on low-selenium soils: crucifers > rye grass > legumes > cereals. This trend was unchanged by variations in soil-selenium concentrations and selenium oxidation states.

Ehlig, et al. (1968), More and Coppnet (1980), Singh (1982), and Bainbridge (1988) have reported on uptake of selenium by several different plant species and found that differences between species are commonly observed. Alfalfa (*Medicago sativa L.*) contained twice as much selenium as bromegrass (*Bromus inermis leyss*), orchard grass (*Dactylis glomerata L.*) or red clover (*Trifolium pratense L.*). The accumulator species had five times as much selenium as alfalfa (see also Chapter 5 and 6).

Selenium is absorbed by plants in both oxyanion inorganic forms, such as selenate or selenite, and organic forms (Johnson, et al., 1967; Stadtman, 1974; Hamilton and Beath, 1963a, b, 1964). Peterson, et al. (1981) reported that selenate is taken up metabolically by plants, while selenite is largely taken up by passive processes, and at lower levels. Selenium accumulator plants may convert unavailable forms of selenium in the soil to forms that are available to non-accumulator plants (Evans, et al., 1968).

Plant selenate and selenite uptake has been considered to be analogous to that of both sulfate and sulfite, respectively. Both forms of selenium are translocated in the xylem sap, selenite selenium being metabolized to selenomethionine and transported to the shoots (Gissel-Nielsen, 1971a). Leggett and Epstein (1956) and Stadtman (1974) indicated that selenate is taken up through the same binding sites in the plant roots as sulfates. They concluded that the two ions are taken up by the same active absorption processes in competition with each other, while selenite is taken up through other sites. In plants, selenium partly resembles sulfur in its biochemical properties and is able to replace sulfur in amino acids as well as in several biological processes (Ganther, 1974).

The distribution of selenium within plants is not well understood. Some studies have suggested selenium is concentrated in growing points, seeds, and roots (Arvy, et al., 1974; Ehlig, et al., 1968), but other studies have shown higher leaf and stem levels and reduced content in seeds (Wu, et al., 1987; Hamilton and Beath, 1963a). Hamilton and Beath (1963 a,b) found that the selenium concentration in the straw was much higher than in the the seed for buckwheat, rye, and wheat. Root selenium concentrations are generally much higher than the tops. Root levels were 2-23 times as high as leaves in a variety of crops in ^{75}Se studies (Johnson, et al., 1967). In Astragali, the opposite seems to be the case, with *Astragalus crotalariae* tops having a selenium concentration 44 times higher than the roots (Rosenfeld and Beath, 1964).

D. The effect of irrigation and drainage on selenium problems

1. Irrigation efficiency

Improving irrigation efficiency is the first step in reducing the magnitude of the problem of selenium in agricultural drainage water (Knapp,1984). The release of selenium from agricultural soils has been encouraged by overleaching to insure full leaching of salts in non-uniform fields. This lack of uniformity can in some cases be improved by laser leveling. Further research is needed on the effects of non-uniformity on optimum crop production (Letey, 1985). Much of the selenium in the seleniferous soils has already been leached from the soil (USGS, 1989) and is now in the ground water. Over irrigation can force this selenium laden water into the drainage systems.

The overuse of water is in part a reflection of inefficient irrigation systems. Recent studies by the State Water Resources Control Board and the Department of Water Resources, Office of Water Conservation showed that one third of the farmers were applying more water than necessary (Central Valley Water Use Study Committee, 1987). Irrigation and drainage practices are strongly influenced by water costs: inexpensive water provides few incentives for efficiency and innovation (Candee, et al., 1985). Widespread adoption of new techniques is unlikely to occur without an economic incentive. Knapp, et al.(1986) found that the water prices were much more important than drainage charges.

Currently, gravity irrigation systems are used on approximately 70% of the irrigated lands in California, while only 5% are irrigated with drip systems (Biswa, et al., 1987). Improvement in the predominant gravity systems can have the largest impact on drainage water volume reductions. Water enters the field at the high end and flows across the field by gravity. The amount of water needed to meet irrigation requirements depends to a large extent on the length of the field, the rate of water application, the duration of the application period, and soil infiltration characteristics (Letey, et al., 1986). Water applications resulting in uniform infiltration with exactly the amounts of water desired are almost impossible. Improvements in application efficiency can be realized with associated costs for equipment, management time, and scheduling. For example, field (furrow or basin) length can be shortened, higher water application rates can be used for a shorter time period, and timing of applications can be modified. Laser-leveled basins with borders that are extremely flat can enable large volumes of water to move quickly and then allow for more uniform infiltration in a shorter time period after somewhat ponded conditions exist temporarily. A predetermined amount of water can be applied in this manner. However, construction costs and laser levelling are expensive when compared to existing irrigation costs.

Improving flow control in surface irrigation can reduce water application volumes. Surge irrigation uses specialized gated pipe systems to intermittently deliver or pulse water to furrows, thereby speeding water travel across the field, increasing application uniformity, and reducing deep percolation and tail water run-off. Another modification of the surge system is cablegation, which automates the intermittent flow of water down a field.

About 10.7 percent of the land irrigated in the San Joaquin Valley in 1980 was irrigated with hand-moved sprinkler systems, only 1.6 percent with mechanically moved systems, and drip irrigation amounted to only 2.5 percent (Calif. Dept. of Water Resources, 1984). Pressurized systems enable much higher irrigation efficiencies and uniformity of application on sloping lands, lands with non-uniform soils, or uneven lands than conventionally managed furrow or basin irrigation systems. This provides the potential to reduce application volumes and drainage volume. There are substantial capital investment costs, maintenance costs, and labor costs involved in pressurized irrigation systems.

Drip systems can provide high uniformity of application and control, but have higher initial costs. Drip systems can be installed on the surface or buried. Subsurface drip can provide added benefits including increased production, weed control, reduction in disease problems, and reduction of drainage flow (Grattan, et al., 1988; Street, 1988). Drip system management with sulfuric acid rinse to maintain flow should minimize selenium problems by increasing acidity and adding competing sulfate ions to the root zone.

The highest drainage flows occur during preplant irrigations and through the period just after planting of crops. These high drain flows are a result from both infiltrated water, which drains out of the field below the surface, and surface run-off. Surface run-off usually contains little selenium, but subsurface drainage waters can have elevated selenium levels and in many drainage systems the two flows are eventually mixed.

Much of the excess water is used to wet soil profiles and to leach salts. Although there is some disagreement about the amount required for leaching salt, some estimates suggest that five percent or less of the applied water is actually required (Letey, et al., 1986).

Partial control of drainage volumes is possible through better irrigation scheduling. Water applications can be timed to correspond more precisely to the needs of the crop as they occur during the growing season. By limiting applications to the amount calculated to be necessary, excess applications can be minimized. Extensive information is necessary to accurately calculate these requirements, including: climatic data, crop needs, soil water status, and established mathematical relationships to predict estimated water needs. Computerized systems of data input and data processing have been developed and can be used to enhance management and scheduling (Letey, et al., 1986). The use of elevated shallow water tables as an alternative summer water source for irrigation can help in water conservation efforts (Agricultural Water Management Subcommittee, 1987).

2. Drainage--tailwater use, reuse, and blending
   Currently farmers have three options to deal with their drainage water when they cannot discharge to surface waters: Allow the water table to rise, reuse drainage water for irrigation (Oster and Rhoades, 1983), or build evaporation ponds (Letey et al., 1986). None of these choices is particularly desirable, and the most attractive option for many farmers, evaporation ponds, may pose serious liability problems as a result of future trace element contamination and cleanup.

   Agricultural drainage water from lands with elevated selenium levels may contain some selenium and also considerable salt. Rhoades (1984) suggested using crop rotations of salt-sensitive and salt-tolerant crops combined with a rotation of saline and non-saline waters. When used properly, no yield losses would occur. This plan may require readily available supplies of both types of water on demand. Separate water delivery systems may be required for this. Blending drainage water with fresh water is another possibility (Dinar, et al., 1985).

   Field research on the effects of reusing drainage water with elevated selenium is underway. Preliminary results suggest that food crop contamination may not be a problem, but only short-term data exists from which long-term effects cannot be determined. No information on the long-term effects of recycling soil selenium and other metals on soils or subsequent drainage effluent is yet available (Burau, et al., 1987). Many of the limitations of drainage water reuse result from concentration of salinity and elements other than selenium which may become increasingly toxic to plants.

3. Acceptable levels of selenium in irrigation water
   The close chemical similarity between selenate and sulfate results in competitive interactions between them for accumulation by plants. This antagonistic interaction was first reported by Hurd-Karrer (1938) and subsequently confirmed by others (Pratley and McFarlane, 1974; Spencer, 1982; Mikkelsen, et al., 1987). Albasel, et al. (1988) found that the selenium concentration in alfalfa was reduced from 83 to 2 µg/g when sulfate was present. This finding supports the new guideline allowing 100 µg/L selenium for irrigated agriculture when using sulfate-dominated saline waters that require a leaching fraction of >0.2 (Pratt, et al., 1988).

   In field trials in the west side of the San Joaquin Valley, Grattan, et al. (1987) measured selenium uptake accumulation by melons. They reported that the estimated daily dietary intake of selenium from these melons and tomatoes would be relatively low, only 6 to 8 µg, as a result of competitive interactions with sulfate which reduce plant uptake of selenium (See also Chapter 3).

   A new approach for the selection of recommended maximum concentration of selenium in the irrigation waters for the west side of the

San Joaquin Valley was submitted to the State Water Resources Control Board by Pratt, et al. (1988). This guideline enables recommended maximum concentrations of selenium in water to be established for various crops, soils, and irrigation systems based on projected uptake. The recommended maximum concentration of selenium in sulfate-dominated irrigation waters of the west side of the San Joaquin Valley is 100 µg/L.

The lack of drainage outflow from the San Joaquin Valley may require reassessment of cropping systems in the area. As regulatory actions place limits on drainage water quality and quantity, growers may be forced to manage water more efficiently and to rely more heavily on improved irrigation systems, alternative crops and cropping systems, and water reuse.

More extensive analyses of drainage water reduction and water conservation can be found in California Department of Water Resources (CDWR) (1984), Willey (1985a,b, 1987), Caswell and Zilberman (1986), Boyle Engineering (1986), Central Valley Water Use Study Committee (1986), University of Calif. Committee of Consultants (1987), Cervinka et al., (1987), San Joaquin Valley Drainage Program Committee (1987), Agricultural Water Management Subcommittee (1987), and State Water Resources Control Board (1987).

E. Cropping system effects on selenium movement and mobility

1. Management of the root zone

Cultural practices which influence root zone soil properties are especially important in selenium management. Conventional management practices have largely relied on addition of soil amendments, such as gypsum, and deep ripping to ameliorate water and root penetration problems which are often associated with salt-affected soils. Providing growers with a wider array of management alternatives has been limited by our limited understanding of the root zone environment and the effects of conservation tillage, alternative irrigation systems, and soil amendments (including organic matter) on soil biota and soil properties. While several investigators have examined rooting patterns of crops under field conditions (Grimes, et al., 1975; Lonkerd, et al., 1979; Hoffman, et al., 1984a, b), the ability to predict the effective rooting volume (ERV) utilized by a crop on a given soil is difficult. This is particularly true for innovative irrigation methods such as deep pipe drip systems (Sawaf, 1980). For example, studies of water use patterns in the North Central Plains have demonstrated that safflower used more soil water to greater soil depths per year than any other crop (Cassman and Rains, 1986) and has been used in rotations to help lower the water table. Unfortunately safflower is a host for thrips which can move from safflower to alfalfa and cotton (Freeman, 1988).

Alfalfa was a close second to safflower in use of soil water in the above study, and is a common component of cropping systems in the San Joaquin Valley. Alfalfa may be more effective at using ground water than safflower, as it is longer lived and may deplete existing soil water supplies from progressively deeper soil depths over several years (Brown and Miller, 1978). Alfalfa cultivars were found to differ in the ability to deplete stored water in the soil profile (Black, et al., 1981); these differences in water depletion were not related to dry matter production. The critical ERV for a specified crop cultivar depends on a set of at least four soil parameters which are often nonuniform: soil water storage, fertility, compaction, and salinity. These characteristics vary in time, down a soil profile and across a field (Lonkerd, et al., 1979; Hoffman, et al., 1984a,b).

Management of selenium levels in drainage water will depend in part on water passage through the root zone. Dinar, et al. (1985) concluded that the high variability in infiltration rates across farmers' fields may explain why growers use a much higher leaching fraction than is theoretically required. Growers apparently apply more water than needed to insure that less impermeable patches within a field are also leached. In many cases, these patches with low infiltration rates represent a relatively small portion of total field area. Major innovations, such as laser leveling, may have conflicting short- and long-term effects, especially when subsoil is exposed. Improved leveling will facilitate the control of water flow across a field, but may also increase the nonuniformity in infiltration rates within the field if levelling exposes a more variable soil pattern.

2. Fertilizer

The addition of phosphate fertilizers may cause an enrichment in the overall selenium content of the soil, since selenium is slightly enriched in phosphate rocks (0.02-30 µg/g; Gissel-Nielsen, 1971b). The addition of sulfates can reduce the uptake of selenium by plants through competitive interaction between selenium and sulfur. The use of nitrate fertilizer can lead to nitrate pollution in the drainage water. The nitrate in soil can slow the reduction of selenium to more inert forms in the sediments and soils, increasing the risk of ground water contamination (Benson, et al., 1988).

3. Organic matter

Soil organic matter content varies considerably among fields with similar soil types in the San Joaquin Valley (Cassman and Rains, 1986). Increased organic matter content in soil tends to counteract the unfavorable affects of exchangeable Na, improves solid structure, and reduces slaking (U.S. Salinity Laboratory Staff, 1954). Russell (1973) suggests that maintenance of decomposable organic matter levels increases soil permeability when irrigation water with a high sodium adsorption ratio (SAR) is used on calcareous soils. Apparently, the higher CO_2 concentration in the soil atmosphere from active microbial populations lowers the pH of the soil solution. This results in increased solubility of Ca^{2+}, lowering the SAR of the soil solution in the root zone.

Crop residue management and cover crops may provide useful management options in the seleniferous soils of California. Crop residues can increase water infiltration, improve soil moisture storage, and provide organic matter energy substrates which soil microorganisms can exploit to increase volatilization of selenium from the soil.

Returning crop residues to the soil has been found to improve physical and chemical properties including soil organic matter, soil nitrogen, soil carbon, available phosphorus, exchangeable potassium, nitrogen mineralization and dry aggregate soil structure (Black, 1973). The addition of straw mulch to a bare fallow salt-affected soil significantly altered the chemical characteristics of these soils. Increased microbial activity decreased the pH of the soil, enhanced nitrate concentration and increased solubility of calcium carbonate. A decrease in pH and an increase in mobile Ca^{++} are two factors involved in reclamation of saline/alkali soils (Paskhina, 1983). These processes will all decrease the availability of selenium.

Crop residue management can also significantly influence water infiltration (Mazurak, et al., 1955). This could conceivably reduce the demand for irrigation water by reducing evaporation and runoff. Williams (1966) reported a 34 percent and 225 percent increase in water infiltration rate in untraveled and traveled furrows, respectively, after 6000 lb/acre of corn crop residue was incorporated in a Yolo loam. Increases of water infiltration rates in California from cover crops are shown in Table 2.4.

4. Cropping systems

Cropping systems and rotations can be used to further reduce ground water problems (Cassman and Rains, 1986). Cropping systems are patterns and sequences of crop production, resource use, and crop management over time and space on a given farm unit. Three types of cropping systems are found on irrigated soils prone to selenium problems in California: field crop systems, vegetable and melon cropping systems, and perennial fruit and nut systems. Of these, irrigated field crop systems predominate. Cotton is the most common crop. Crop rotations vary from farm to farm and area to area and are comprised of an irregular sequence of dominant and secondary crops (Table 2.5).

The dominant crop commonly provides a better return than secondary crops and a grower manages a crop rotation to maximize production and returns from this crop. The dominant field crop in the selenium problem areas is cotton. Secondary crops include alfalfa, tomatoes, sugar beets, melons, barley, and dry beans (Cassman and Rains, 1986).

The factors which determine the need to rotate out from a dominant crop vary, depending on cropping system and region. On the west side of the San Joaquin Valley soils growers rotate out of cotton, tomatoes, melons, or vegetable crops when disease or weed pressures reduce yields.

Table 2.4. The Characteristics of Five Green Manure Crops and Their Effect on the Infiltration Rate Measured over a 28-Month Period, 1959-60.

Green manure	Date of incorporation	Stage of tops	Dry Weight lb/acre	Mean infiltration rate in./hr
Barley	April 30	Milk	7,120	1.40
Cereal rye	May 23	Milk	9,860	1.35
Annual ryegrass	April 30	Heading	3,820	1.30
Soft chess	April 30	Heading	3,980	1.13
Mustard	March 28	Blooming	4,090	0.89
Control	----------	------------	--------	0.73
LSD 0.05	----------	------------	1,250	0.18

Source: Williams, 1966

There is some evidence that use of subsurface drip may enable growers to maintain the dominant crop for longer periods (Street, 1988).

Although rotation intervals are irregular, the pattern of dominant secondary crop rotations in the San Joaquin Valley has proved be relatively consistent over the past 40 years (Cassman and Rains, 1986). The availability of low-cost/low-salt content water was responsible for a large shift in cropping patterns in the selenium problem areas. Construction of the Central Valley project in the 1940s and the California Aqueduct in the late 1960s provided good quality canal water to large areas in the San Joaquin Valley. There has been a steady increase in the proportion of acreage in crops with a potentially higher return or lower risk. This trend has increased water use and drainage requirements and greatly affected the salt balance in these soils. Much of this shift has also been influenced by federal price support programs.

Federal subsidies provided much of the impetus for expanding cotton acreage in the San Joaquin Valley, which doubled between 1929 and 1964, while the nationwide acreage decreased 68% (Jelinek, 1982). More than 85% of the cotton acreage in the San Joaquin was grown under federal subsidy programs in 1986 compared to only 34% in 1984 (Hanemann, et al., 1987).

The current pattern of crop use in a representative irrigation district is shown in Table 2.6.

The adoption of traditional rainfed crops, primarily small grains which were grown on 235,000 acres of the Westlands Water District in 1958 (Wilson, 1976), or the introduction of new crops and crop rotations which require less water may also be useful. The genetic improvement of present crops to minimize selenium (salt and boron) problems are also worthy objectives but are unlikely to be of immediate value. The production of perennial crops, e.g. trees for fiber or biofuel, is particularly

Table 2.5. Common Crop Rotation Pattern for the West Side of the SJV

Year	Crop
1	Cotton
2	Cotton
3	Wheat[a]
4	Cotton
5	Cotton
6	Cotton
7	Tomato
8	Wheat[a]
9	Cotton
10	Cotton

[a] Wheat planted in late fall of the proceeding year and harvested in June or July of the following year results in a summer fallow period.
Source: Cassman and Rains, 1986.

attractive as the deep roots of these plants can enable them to rely more heavily on ground water. Eucalyptus may be a good candidate for production in these areas (Standiford, 1988).

The development of integrated systems of production using water several times before discharge or treatment is also promising (Rhoades, 1984; Cervinka, 1988). Clean water would be used on a salt-sensitive crop, the drainage water and tail water from this crop would be used to irrigate a more tolerant crop, i.e., cotton, the drainage and tailwater from this crop would then be used for eucalyptus production, and the concentrated water left after this crop would then be used for a final halophytic crop. The small volume of water left after that would be disposed of or treated.

F. Reducing the adverse environmental impacts of selenium derived from agricultural operations

1. Education

Education of farmers and water managers is perhaps the key step to reduce water use and reduce the drainage problem (Agricultural Management Subcommittee, 1987). This might include increased educational efforts by the University of California, the San Joaquin Valley Drainage Program, the irrigation districts, and the Soil Conservation Service. The integrated management of crops is particularly important, so the financial benefits of more efficient practices such as subirrigation include pest control (Grattan, et al., 1988) as well as water savings and drainage reduction. Any one benefit by itself may be insufficient to justify the adoption of more expensive and efficient systems while the combined benefit may promote this type of innovation.

Table 2.6. Water use in the Westlands Water District during a representative year.

Fraction of total water	Crop	Area	Water use per acre	Water use per year
Percent		acres (1000s)	acre-feet/acre	acre feet (1000s)
58	cotton	286	2.13	609
8	tomatoes	44	1.83	81
8	alfalfa-hay	19	4.18	83
8	afalfa-seed	24	3.53	88
5	sugar beets	16	3.03	51
3	wheat	23	1.53	35
2	dry beans	10	1.86	19
2	barley	15	1.21	18
2	melons	20	0.86	17

Source: Westlands Water District, 1985.

These benefits will probably need to be demonstrated on-farm in a comprehensive research program before they will be widely adopted by the farming community.

2. Financial incentives

> *California's agricultural economy is currently faced with rising water prices and falling product prices. Growers respond to changes in these relative prices by managing their water more carefully, by shifting away from water-intensive crops, and in some instances, by taking land out of production. These decisions usually result in the saving of water as a consequence of abandoning some beneficial use because it is no longer an economical use.*
>
> *Letey and Vaux, 1987*

Any attempt to reduce selenium contamination of drain water should consider the economic incentives that currently drive the system. More complete discussion of external costs and total cost to society is essential. Alternative treatments should be selected on a basis that provides net benefits to society--rather than net costs. Much of the current discussion has focussed on adding a new layer of economic incentives for treatment of selenium drain water rather than adapting strategies and incentives that minimize water use and drainage. It may be more appropriate to consider a broader range of options with a more complete consideration of economic incentives and external costs. The economic return to society from alternatives such as agroforestry, dryland grain, recreational hunting and fishing, or grassland need to be better understood. The fine tuning of programs such as the Conservation Reserve Program to include ground water management and selenium control should also be considered. A more comprehensive selection of groups need to be involved in the discussion of these problems. The taxpayer, as is often the case, is a forgotten voice in these deliberations.

One option that provides incentives for saving water is the adoption of tiered water prices. Rather large reductions in drainage volume can be induced by tiered pricing (Letey, et al., 1988). An investigation of the use of tiered pricing is now underway on the West Side of the San Joaquin Valley (Agricultural Water Management Subcommittee, 1987).

The development of more open water transfers and marketing may provide the same type of benefits with minimal government interference. This would enable conserved water to be sold. Several legal questions remain to be answered before this open marketing can take place (SJVDPC, 1987).

Revisions of water contracts to districts to encourage conservation would also be desirable. Current contracts often require payment of a specific fee irrespective of grower demand. These should be changed to encourage conservation (Agricultural Water Management Subcommittee, 1987).

Alternatives such as agroforestry, dryland grain, recreational hunting and fishing, or grassland might provide better returns to farmers and land owners than traditional cropping patterns, particularly if regulatory costs are explicitly considered.

3. Non-monetary incentives
The development of water quality standards and regulations encourages compliance with laws and regulations to maintain water rights, ensure adequate irrigation water, to maintain production over the long-term, and to maintain a positive image in the legislature and the media. These goals can provide the incentive to incorporate technology that will minimize risk when other changes are undertaken. Regulations, such as the Title 23, Subchapter 15 of the California Administrative Code regulating disposal of liquid waste, can also provide incentives for conservation and reduction in drain volume (Agricultural Water Management Subcommittee, 1987). The desire to avoid risk, including the risk of future liability and litigation, may also be important (Merrill, et al., 1983).

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Chapter III. Selenium and Human Health

One of the most exciting effects of selenium on health is selenium's anticarcinogenic effect against experimentally induced cancer in several animal systems.

R. J. Shamberger, 1983

A. Introduction

Selenium is both an essential nutrient and potential toxicant. Many questions remain about the amount of selenium required for optimal health and maximum allowable levels of exposure for various forms of selenium in the diet. The possible risks or benefits from environmental exposure to various selenium gasses and compounds are also not well understood. The most common concern in California is the possible impacts of elevated levels of selenium in food and water on human health. This issue is especially important because the allowable or desirable exposure level determines permissible food and water concentrations and the range of acceptable options. The uncertainties described in this chapter are related to the problems of human epidemiological studies in general and selenium in particular.

B. The human selenium cycle

Probably the most important problem in establishing what is safe and desirable is the complexity of the human body and its regulatory systems. Interactions between factors such as diet, stress, and general health affect the need for and retention of selenium. Selenium nutritional status is also affected by dietary exposure to other metals, vitamins, proteins, fats, sulfur levels, and environmental exposure to pollutants and other compounds, such as synthetic antioxidants (Combs and Combs, 1986).

Selenium uptake and nutritional effects are also related to the form of selenium ingested. Some forms are very bioavailable while others are much less readily used by the human system. Total uptake of selenium is a function of total selenium in the food, its bioavailability, and the absorption rate. This picture is further confused because retention is influenced by the existing body selenium status and dietary levels.

Some of the common sources of dietary selenium are shown in Table 3.1.

Food processing can affect selenium levels, although in general, home cooking methods such as boiling, baking, and broiling have little effect on the selenium level of food (Higgs, et al., 1972). Milling and commercial drying of grain can lead to substantial losses of selenium (Combs and Combs, 1986). Wheat, for example, lost up to 40% of total selenium during milling and 23% during drying at 100°C in the preparation of a breakfast cereal.

The individual selection of diet must also be considered. This is especially important in the U.S. where individual variation in diets is very high. Welsh, et al. (1981) found that although the mean selenium intake

Table 3.1. Selenium in the human diet

Food	Fraction bioavailable	Concentration
	percent	μg/g
Typical diet, US[1]	--	0.11
Animal products	typically <25	--
Plant products	typically 60-90	--
Brewers' yeast	89	1.1
Corn meal	86	0.1-0.2
Wheat	71	0.2-1
Tuna	22-47	0.5-1.5
White bread	--	0.28
Whole wheat bread	--	0.67
Mushrooms	--	0.13
Round steak	--	0.34
Organ meats	--	1.0
Oysters	--	0.67
Garlic	--	0.25
Selenomethionine	37	--
Sodium selenate[2]	74	--
Sodium selenide	42	--
Sodium selenite	100	--
Elemental selenium	7	--

[1] range is substantial.

[2] common form in water and soils of California.

Sources: Combs and Combs, 1986; Cantor, et al., 1975a, b; Levander, 1976; Morris and Levander, 1970.

was 81 μg/day, intake ranged from over 275 to less than 25 μg/day in a study of Maryland residents.

The human body is apparently capable of adjusting its selenium levels over time. It responds to over-exposure by increasing excretion and to deficiency by lowering selenium loss rates (Combs and Combs, 1986). Selenium is absorbed in the intestinal system relatively well at low doses, with up to 90% of dietary selenium retained and only 10% passed through (Combs and Combs, 1986). Selenium is primarily lost through excretion in urine, although with very high doses respiratory losses also become important. This leads to the characteristic "garlic breath" reported with selenium toxicosis (Anderson, et al., 1961).

Understanding selenium nutrition is made more difficult by the non-specific symptoms of marginal selenium deficiency or excess which can be confused with each other and with many other diseases (Koller and

Exon, 1986). It is very difficult to assess effects such as increased susceptibility to infection and cancer, muscle aches, fatigue, and headaches. Although some lessons have been learned by studying people living in areas with selenium levels that are considered deficient or potentially hazardous, differences in diet and environment limit their value.

Nutritional studies with animals are the most common method of assessing diet and health interactions but the results are not always consistent with what has been observed with humans. Small differences in intestinal systems, diet, and metabolism can make relatively large differences in selenium response.

The effect of selenium also depends on the form in which it occurs in food or water. Most of the studies on selenium have evaluated the effects of inorganic selenium salts, because they are relatively easy to obtain and quantify. The organic forms of selenium, which appear to be more active, are much more difficult to analyze and have been used less often. Much more research is needed to understand the bioavailability and possible benefits and risks of the many forms of organic selenium (NRC, 1976). The following descriptions of the effects and risks of selenium deficiency and excess should be considered with these limitations in mind.

C. Selenium as an essential nutrient

Although studies in the late 1950's showed that selenium was an essential nutrient for animals, the application of these results to humans was not readily accepted because of earlier concerns that selenium was a carcinogen (Nelson, et al., 1943). This led the Food and Drug Administration to prohibit the use of selenium supplements for humans. This concern was gradually eased following a series of studies in the late 1960's and 1970's. Tinsley and associates (1967), for example, reported no carcinogenic effects for selenium in a comprehensive study using rats. These studies eventually led to the realization that humans were also susceptible to selenium deficiency diseases.

Chinese investigators subsequently showed that humans develop selenium deficiency diseases much like other mammals (Yang, 1979; Keshan Disease Research Group, 1979a; Yang, et al., 1983). Keshan disease is a cardiomyopathic disease found in several selenium-deficient regions of China. The peak incidence of the disease occurs in the winter months. Adding 15 µg/g of sodium selenite to table salt has been effective in preventing the disease (Keshan Disease Research Group, 1979b). Affected individuals had blood selenium levels of 0.01 µg/ml compared to 0.07 µg/ml in blood for residents of selenium-deficient areas in New Zealand and a typical blood level of 0.15 µg/ml in the (Frost, 1981). Symptoms of selenium deficiency are probably more commonly observed in China because of the reliance on locally grown food, raised on selenium-deficient soils, and more restricted diet.

A second selenium deficiency disease, Kashin-Beck Disease, occurs in eastern Siberia, northern Korea and parts of China (Combs and Combs, 1986). This was first observed in 1849 and described by Kashin in 1859 and Beck in 1906 (Mo, 1986). It primarily affects bones and cartilage and results in shortened fingers and toes, enlarged joints, and dwarfism in extreme cases (Mo, 1986; Combs and Combs, 1986). Both Kashin-Beck and Keshan disease occur together in several areas of China but the reasons for their different symptoms are not understood.

New Zealand has also provided considerable insight on the effects of subclinical selenium deficiency. Selenium deficiency diseases of animals are common in New Zealand and some symptoms of selenium deficiency also occur in humans. Ranchers reported relief from the symptoms of selenium deficiency when they treated themselves with sheep drench providing 1 mg of selenium per dose (Robinson, 1975). Studies of populations in areas with selenium-deficient soils in Europe have also led to improved understanding of selenium requirements. Vegetarians and patients on parenteral nutrition are the primary groups with low selenium status in these areas (Abdulla, et al., 1982; Roekens, et al., 1986).

Selenium is involved in immune system response and its deficiency may manifest itself in increased susceptibility to infection and disease, including cancer (Kiremidjian-Schumacher and Stotzky, 1987). These effects are difficult to assess without carefully controlled long-term studies of large populations. Enough is known to say that there is a definite relationship between selenium deficiency and cancer. Shamberger and Frost (1969) reported that a study designed to correlate high levels of selenium with high cancer rates had instead suggested that there are "possibly protective effects of selenium against human cancer". A detailed survey of areas with very low cancer rates (Blondell, 1983) found that higher levels of dietary selenium were associated with the lower incidence of cancer. This relationship has subsequently been confirmed in other studies (Salonen, et al., 1984; Clark, 1985; Combs and Combs, 1986).

Because the carcinogenic process itself may influence selenium status (Robinson, et al., 1979; Klasing and Schenker, 1988), studies of cancers not presumed to affect selenium levels (e.g., skin cancers) may provide the best understanding of the relationship between selenium status and cancer (Combs and Clark 1985; Willett and Stampfer 1986). Clark, et al. (1984) compared blood selenium levels in 190 skin cancer patients and 60 controls without cancer. When the lowest and highest decile of plasma selenium in patients with skin cancer was compared with current patient controls, the probability of skin cancer in persons with the lowest plasma selenium levels was more than four times as high as that of skin cancer in persons with the highest plasma selenium levels.

A prospective case-control study (Salonen, et al., 1984) indicated that selenium deficiency (defined as serum levels less that 45 μg/L) was associated with an increased risk for nonhormone-dependent cancers in middle-aged persons. A subsequent prospective study confirmed this association (Salonen, et al., 1985). Serum selenium levels were lower than controls in some cases, with the risk for development of cancer for subjects in the lowest quintile of serum selenium twice that of subjects in the highest quintile in patients in a hypertension study (Willett, et al., 1983).

The effects of selenium on cancers that may be hormone-related and may therefore, affect selenium status may also be very important. Schrauzer, et al. (1980) showed that selenium reduces breast cancer in mice. This was further confirmed by Ip and White (1987) who found little difference in the protective effects of selenite, selenate, selenium dioxide, selenomethionine, and selenocystine. Blood selenium levels in women with breast cancer were significantly lower than controls (McConnell, et al., 1978). Schrauzer, et al. (1987) found blood selenium levels of healthy women in both Japan and California were significantly higher than women with breast cancer and that "low dietary selenium intakes may increase the risk of fibrocystic disease development". Fibrocystic disease leads to a three-fold increase in the risk of breast cancer (Spratt and Donegan, 1968). Studies have also showed a strong relationship between selenium status and the extent and progression of cancer (Broghamer, et al., 1976). Lewko and McConnell (1987) demonstrated the inhibiting or toxic effects of different forms of selenium on human breast cancer cells in tissue culture.

Selenium may provide protection from cancer as a result of increased "trapping" of chemical forms of carcinogens (Ip and Daniel, 1985; Van Fleet and Watson, 1984; Watson, 1985). The anti-oxidant role of selenium may also be important, as glutathione peroxidase with selenium in the active site reduces hyperperoxide levels, which would reduce oxidation reactions (Watson and Leonard, 1986). Lewko and McConnell (1987) suggest that part of the protective action of higher levels of serum selenium on breast cancer may reflect decreased estradiol binding, which could be of considerable significance since induction of breast cancer appears to be very sensitive to the endocrine environment (Kennedy, 1974). Schrauzer, et al. (1987) calculate a 4-5 fold increase in the risk of breast cancer with a drop in daily selenium intake from 250 to 125 μg/g per day. Clinical trials are currently being performed to test the therapeutic benefit of selenium compounds for cancer prevention (Clark and Combs 1986; Sestili 1984).

Ip (1987) found that higher levels of selenium supplementation could offset much of the increased cancer risk of high fat diets. Supplementation with a diet containing 5 μg/g selenium provided better protection than the same diet with 2.5 μg/g. The diet with just 2.5 μg/g selenium reduced the total number of tumors more than one third at the high fat level, while the diet with 5 µg/g reduced the total number of tumors by two thirds at the high fat level.

Selenium may also be of value in the prevention and treatment of a number of other diseases. Research has been limited and much evidence is anecdotal or must be inferred from studies with other mammals. Sufficient information is available to suggest that selenium may play a role in the treatment or prevention of rheumatoid arthritis, some types of arthropathy and joint pain, chronic pancreatitis, weakness and easy tiring, depression, atherosclerosis, infections, peridontal (gum) disease, retinal vascular damage and retinopathy associated with diabetes, cystic fibrosis, and some types of heart disease (NRC, 1976, 1983; Wallach and Garmaise, 1979; Frost, 1981; Oldfield, 1980; Spallholz, 1981; Shamberger, 1983; Aalbers and Houtman, 1985; Kondo, 1985; Meisel and Wouters, 1985; Tolonen, et al., 1985; Boyne and Arthur, 1986; Brown, et al., 1986; Combs and Combs, 1986; Rose, et al., 1986; Watson and Leonard, 1986; Hempel, et al., 1989). Selenium deficiency has been linked to a reversible cardiomyopathy in humans (Reeves, et al., 1989).

The relationship between selenium deficiency in livestock and infertility is well-established (Shamberger, 1983) and similar results might be expected in humans. The traditional use of peat treatments for infertility (Levathes, 1987) may reflect observed benefits from exposure to the selenium contained in the peat; concentrations of several µg/g have been observed (Wilber, 1983). Other anecdotal accounts of benefits from peat baths, e.g., relief of rheumatism (Levathes, 1987), and hot springs, may also be related, at least in part, to selenium.

The importance of selenium in immune system response, and the observed 50% depression of selenium levels in Acquired Immunodeficiency Syndrome (AIDS) patients compared with non-AIDS controls suggests the benefits of selenium supplementation for AIDS patients (Dworkin, et al., 1986). The use of selenium supplements for AIDS Related Complex patients and people with HIV antibody response would also appear worthy of investigation.

Deficiency effects related to infection may be of particular importance to infants. The selenium status of infants is often poor and selenium deficiency would be expected to occur in infants more often than adults. Selenium levels are particularly depressed in low birth weight premature babies (Lockitch, et al., 1989). Studies in Belgium, Finland, and Germany have shown a decline in selenium during the first year of life (Combs and Combs, 1986). This is related to the very low selenium content in infants' food (Table 3.2).

Infants are at special risk of selenium deficiency because the selenium content of whole blood and plasma is lower in pregnant women (Butler,

Table 3.2. Selenium levels in infant foods

Food	Area	Concentration
		µg/g fresh wt
Breast milk, >10days	NZ*	0.008
	US	0.020
Colostrum, <4 days	US	0.041
Milk based formula	US	0.011-0.039
Soy-casein	US	0.014-0.015
Parenteral solution, amino acid	US	0.001
Casein hydrosolates	US	0.019-0.037
Strained green beans	US	0.005
Strained carrots	US	0.002
Strained peaches	US	0.004
Rice	US	0.021
Chicken	US	0.107

*Selenium-deficient area.
Sources: Morris and Levander, 1970; Combs and Combs, 1986.

et al., 1982). Plasma selenium started to decline in the second month and whole blood selenium in the fourth. Selenium reached its lowest level shortly before birth. In women studied in Oregon, the average blood selenium level dropped from 0.12 µg/ml in the second month to 0.07 µg/ml in the eighth and ninth months, a decrease of more than 40% (Butler, et al., 1982). Although the significance of this is uncertain, this is below the blood selenium level for cattle, 0.08 µg/ml, found to prevent reproductive problems, provide resistance to disease, and prevent selenium deficiency disease (Nelson and Miller, 1987; Norman, 1987). Other studies have also reported low blood selenium levels during pregnancy. The third trimester plasma serum selenium levels in pregnant women are lower by 10-45% (Combs and Combs, 1986).

Premature babies are especially vulnerable to selenium deficiency because they are often born with very low selenium levels (Gross, 1976; Haga and Lunde, 1978; Amin, et al., 1980; Pleban, et al., 1983). They may also get little selenium in parenteral solution. Infants (1-30 days) receiving parenteral feeding solution experienced decreases of serum selenium of 50% in 3-4 weeks and 66% in 5 weeks (Bratter, et al., 1986).

Formula-fed infants who may receive only 25-35% as much selenium as breast fed infants, are particularly likely to develop selenium deficiency (Gissel-Nielsen, et al., 1984). The protein base of infant formula may also affect the uptake of selenium (Lonnerdal, 1985; Solomons, et al., 1986). Casey and Hambridge (1985) suggest that infant formula should be supplemented with selenium.

Sudden unexpected death has been correlated with selenium and vitamin E deficiency in piglets and has been suggested as an agent in

Sudden Infant Death Syndrome (SIDS) (Money, 1970; Geertinger, 1968). SIDS is responsible for between 7,500 and 10,000 deaths each year in the United States. SIDS is defined as the sudden unexplained death of an apparently healthy infant, usually occurring during sleep, which remains unexplained after a thorough post-mortem examination (Keens, 1987). It is the leading cause of death for infants from the age of 1 month and 1 year (Keens, 1987). The incidence of SIDS peaks two to four months after delivery and is rare after nine months (Giulian, et al., 1987).

SIDS victims have been found to have lower blood selenium levels, although liver selenium concentrations were not significantly different than non-SIDS infants in the limited analysis that has been done (Rhead, et al., 1972). SIDS livers contained significantly greater concentrations of iron and lower concentrations of retinyl esters (Money, 1978). Tapp and Anfield (1975) reviewed vitamin E levels in a small number of SIDS cases and found them to be considerably lower than in the controls. Vitamin E and selenium appear to perform overlapping functions (Schwarz and Foltz, 1957; Reed, 1980). If selenium is limited, then vitamin E status may become more critical. However, Rhead (1977) presents evidence that the selenium and vitamin E levels were normal in both SIDS and non-SIDS infants.

The iron in many commercial baby formulas has been found to destroy some forms of vitamin E (Reed, 1980). Unsaturated fats have also been found to induce vitamin E deficiency diseases in animals and poultry (Century and Horwitt, 1960). The combined effects of high dietary levels of iron and unsaturated fats may depress vitamin E levels and contribute to expression of selenium deficiency symptoms. Cadmium exposure may also contribute to selenium/vitamin E deficiency because cadmium may combine with selenium to make the selenium unavailable (Magos and Webb, 1980). Godwin, et al. (1978) found that copper, and to a lesser extent iron, had adverse effects on selenium-deficient rats. It is possible synergistic effects develop between several of these factors.

Money (1978) suggested that the pro-oxidative stress of an iron oversupply, combined with reduced anti-oxidant protection caused by low vitamin E status, may be a factor in SIDS. Given the interrelationship of vitamin E and selenium this may also reflect inadequate selenium. However, insufficient data are available to confirm this. The peak incidence of SIDS correlates well with minimum total hemoglobin associated with normal infant anemia (Naeye, 1980), and selenium deficient rats exhibit defective utilization of haem (Correia and Burk, 1983). Selenium supplementation proved to be partially effective in protecting against the pro-oxidative effects of excessive dietary iron. Using a milk based formula with 0.0048 µg/g Se (vs 0.0034 µg/g soy formula) was effective in reducing *in vitro* H_20_2-induced hemolysis stimulated by an iron enriched, 20 µg/g, formula (Rudolph, et al., 1981).

If the relation between SIDS and selenium deficiency is real then the highest risk should be for a premature baby born to a poorly nourished mother who smokes and drinks alcohol in an area with low selenium levels in food and water. Use of selenium-deficient parenteral solution or formula should also be implicated. A relationship with low vitamin E intake, high iron, cadmium, or copper intake, and high unsaturated fat consumption would also be expected. If nutritional factors are involved it should be expected to show a continuing relationship within a family and little or no differences between maternal and paternal twins. Keens (1988) reports several studies that suggest the incidence of SIDS is the same among fraternal and maternal twins, implicating environmental rather than genetic causes. There is some evidence that subsequent siblings face a slightly increased risk of SIDS, but the differences are not as large as first suspected (Peterson, et al., 1980; Beal, 1987; Keens, 1987; Davis, nd; Keens, 1988).

The incidence of SIDS correlates with maternal smoking, low birth weight, prematurity and retarded growth development (Naeye, et al., 1976; Lewak, et al., 1979; Standfast, et al., 1980; and Peterson, 1981). Several studies have suggested that SIDS is more common in bottle-fed than in breast-fed babies (i.e., Carpenter and Shaddick, 1965), but this may simply reflect other factors affecting the health of the baby (Biering-Sorensen, et al., 1978). The SIDS rate showed a slight (not statistically significant) increase in Copenhagen from 1956-1971 during a marked decrease in breast feeding (Biering-Sorensen, et al., 1978).

The observed seasonality of SIDS occurrence and the differences between ethnic groups (Goldberg, et al., 1986; SIDS database, 1985) may be related to dietary factors. The increased mortality from SIDS in winter would be expected if selenium status is implicated because selenium deficiency diseases are more common in winter in livestock (Shamberger, 1983), and similar patterns of selenium deficiency disease are observed among people living in the selenium-deficient areas of China (Yang, 1979).

Preliminary attempts to correlate SIDS occurrence with observed patterns of blood selenium nationwide have not shown a strong relationship. This is not surprising given the limited information on blood selenium levels, the large variation of selenium content in self-selected diets, and many complicating factors. It would be very useful to improve the quality of these studies with a careful analysis of geologic formations, selenium content of food and water, and suspected dietary cofactors (iron, copper, cadmium, and fats). A series of case studies in known selenium deficient areas, i.e., Lima, Ohio for example (Scott, 1973), would be very useful. These more detailed studies might determine if there is an above normal incidence of SIDS in selenium deficient populations. A preliminary review of the relationship between areas of probable low selenium in California and SIDS is included later in this Chapter. Although this shows a correlation it does not confirm causation and these results must be considered preliminary until a more rigorous analysis is undertaken.

The occurrence of sudden death among Asian immigrants (Kirschner, et al., 1986; Gilbert, et al., 1986; Munger, et al., 1986; Parrish, et al., 1987), which has also baffled investigators, may be related to selenium deficiency and SIDS. The victims of this syndrome are most commonly recent Laotian immigrants from refugee camps in Thailand. The effects of poor diet in the camps and low selenium in the local food (Keshan and Kashin-Beck selenium deficiency diseases occur in similar geologic zones of the Precambrian shield) may contribute to sudden death after exposure to pro-oxidative stress. Munger (1987) found that this syndrome was also observed in the camps in Thailand. This syndrome becomes rare as residence time in the U.S increases.

Other sudden death syndromes may also be related to selenium status. Lithell, et al. (1987) found that a history of alcohol intemperance, which lowers selenium levels, led to a four-fold increase in risk of sudden death after myocardial infarction.

After the suggestion was made that amyotrophic lateral sclerosis might be related to high levels of dietary selenium, a survey was completed which, as with cancer, showed exactly the opposite. Not enough data are available to make this more than an interesting observation at this time (Gissel-Nielsen, et al., 1984).

There is also increasing evidence that selenium may offer some protection against the effects of aflatoxins (Brucato, et al., 1986), heavy metals (Frost, 1981; Whanger, 1981; Olsson, 1986), and other toxins, including organophosphates and pesticides (Wilber, 1983). Omaye, et al. (1978) found that selenium supplements provided protection against paraquat dichloride in rats. Combs and Peterson (1983) found that increased selenium, 0.10 µg/g sodium selenite, in the diet tripled the LD_{50} for paraquat in chicks. Increased selenium intake may, therefore, be desirable in areas with polluted water, contaminated food, or for workers with on-the-job exposure to these types of toxins.

D. Selenium as a potential toxicant

Selenium can be harmful at high doses (Wilber, 1980). The direct effects of selenium toxicosis may often be misdiagnosed because some of the symptoms are also associated with other diseases and even with selenium deficiency. Adverse effects from excessive selenium have been reported in humans in many areas of the world, including China (Frost, 1981), Venezuela (Kerdel-Vegas 1966), and the (Anderson, et al., 1961; Kilness and Simmons, 1985). The symptoms of selenium toxicosis in humans include extreme lethargy, weakness, nervousness, numbing and tingling of the extremities, headaches, dizziness, paralysis, motor disturbance, loss of hair and nails, lesions of the skin and nervous system, nausea, diarrhea, vomiting, liver function disturbance, ridged or poor nails, and garlic breath (Gissel-Nielsen, et al., 1984; Kilness and Simmons, 1985; Fan, 1986; Combs and Combs, 1986).

One of the best documented cases of selenium poisoning involved individuals taking selenium supplements that contained more than 180 times the intended selenium content as a result of a manufacturing error (Anon, 1984). Individuals were taking 27 mg of selenium per day. One individual took these selenium supplements for 33 days despite many signs of selenium poisoning. The patient eventually (temporarily) lost one finger nail and virtually all of her hair, but few permanent effects were observed (Jacobs, 1987). In another case, a fifteen-year-old girl ate 22.3 mg of selenium as sodium selenate with no apparent long-term effects (Civil and McDonald, 1978).

A reduction in selenium intake will usually result in remission of symptoms from selenium poisoning as the body excretes selenium and reduces body selenium levels. However, chronic exposure can lead to permanent damage. No effective treatments for acute selenium poisoning have been found (Combs and Combs, 1986).

Little is known about the health risks of exposure to selenium gasses in natural settings but concentrations are apparently very low. Monitoring at Kesterson Reservoir recorded typical levels of selenium gasses below 50 ng/m^3 (USBR, 1986). It is not known if increasing these rates through volatilization processes could ever lead to health hazards . The health effects of exposure to selenium gasses have not been extensively studied.

Exposure to SeO_2 has been linked to amnestic difficulties, headaches, sleeplessness, irritability, tachycardia, anorexia, substernal burning, inflammation of nasal mucosa, pulmonary edema, irregular menses, menostasis, dyspepsia, epigastric pain, lassitude, garlic breath, and irritation of the eyes, acute burns to eyes in high concentrations, rhinitis, bleeding of nose, and nervous disorders (Hamilton, 1925; Nagai, 1959; Kinnigkeit, 1962; Glover, 1970).

Problems associated with exposure to H_2Se include vomiting, nausea, metallic taste, dizziness, lassitude, and fatigue (Buchan, 1947). H_2Se causes acute irritation of eyes, lungs, and throat, pulmonary edema--with acute cases at less than 0.07 mg/m^3, but no fatal cases of H_2Se exposure have been reported (Glover, et al., 1979). Exposure level should be kept below an average of 0.01 mg/L/8 hr (Gerhardsson, 1984). The 30-day LD_{50} for H_2Se in pigs was 0.001-0.004 mg/L of air (Dudley and Miller, 1937). H_2SeO_3 is also suspected to be hazardous (Combs and Combs,1986).

The gasses evolved by plants, fungi, and animals may entail some risk at higher concentrations; however, the 24 hr LD_{50} for dimethylselenide by intraperitoneal injection was 1300 mg Se/kg body weight in the rat and 1600 mg Se/kg body weight for the mouse (McConnell and Portman, 1952). In one case, researchers were apparently affected by the dimethlyselenide exhaled by the animals given selenate injections (Motley, et al., 1937). Workers experienced severe pharyngitis and bronchitis and these symptoms recurred after minimal reexposure to selenate dust--possibility as a result of allergic sensitization. Further research on the effects of inhalation exposure to selenium gasses is needed.

There is also some concern about the effect of selenium exposure on reproduction (NRC, 1976). Although no embryotoxic or teratogenic effects were seen in hamsters given intravenous sodium selenite, apparent reproductive system disturbance from high exposure to selenium compounds has been noted in many species (NRC, 1976; Combs and Combs, 1986; Fan, 1986). These are commonly observed with high doses of organic selenium compounds and may involve the replacement of sulfur with selenium in amino acids. However, sodium selenate appeared to offer protection against mutagenic problems (Shamberger, 1983). Barlow and Sullivan (1982) concluded that selenium has a low degree of teratogenicity in rodents but that not enough information was available to evaluate the effect of selenium compounds on human mutagenicity. Excessive amounts of selenium may also increase susceptibility to aflatoxins and carcinogens (Newberne, 1984; Watson and Leonard, 1986). Selenium nutrition requires a careful balance between many different factors.

However, the effects of substantial doses of selenium (up to 998 μg/ day) from drinking water appear to be minor (Valentine, et al., 1978, 1981, and 1987). Tsongas and Ferguson (1977) also reported no differences in health indicators in a comparison of matched communities with drinking water selenium levels of <16 μg/L and 50 to 125 μg /L, respectively. Relatively high intakes of selenium supplements have been reported without adverse health effects (Klasing and Schenker, 1988). Anecdotal claims of selenium supplementation of 700 μg/day for several years and yeast-selenium in doses up to 2,000 μg/day for prolonged periods without consequence have been cited (McCarty, 1984). Selenium levels of 225 μg/L in the water should pose little hazard for individuals receiving only 100 μg/day from the rest of their diet (Combs and Combs, 1986).

E. Dietary recommendation

The primary source of selenium for most people is food. This dietary selenium is transferred by the blood to the muscle tissue and liver where most of it is stored. The selenium in the liver can be mobilized if low blood selenium concentrations develop.

There is considerable disagreement over desired levels of selenium intake in diet. Although the current NRC recommended level of selenium in the diet is from 50-200 μg/day (NRC, 1980) others feel higher levels are desirable (Passwater, 1980; Koller and Exon, 1986). The NRC recommendation is based on the results of animal studies and is primarily concerned with preventing deficiency diseases. A selenium-balance trial of healthy young North American males determined that they required 70 µg/day to maintain their selenium balance, substantially supporting the NRC recommendation (Levander, et al., 1981). This amount is considerably higher than the estimate of 20 µg/day required for selenium balance in young women in New Zealand (Stewart, et al., 1978). It may be attributed to a lower body selenium level and smaller size, differences in the bioavailability of selenium from different food sources, and adjustments of the human system to different dietary levels of selenium.

Selenium status may be affected by diet, disease, drugs, smoking (decreases blood selenium levels), alcohol consumption (decreases blood selenium levels), and activity (Lloyd, et al., 1983; Dutta, et al., 1983; Dworkin and Rosenthal, 1984; Combs and Combs, 1986). Dietary recommendations should be considered as general goals rather than specific "universal" prescriptions.

Dietary standards for maximum dietary levels are as difficult to develop as those for minimum requirements. They depend on the same complex set of factors and insufficient information is available about many aspects of the interactions and behavior of selenium in humans. Combs and Combs (1986) suggest an upper safe limit of 775 µg per person per day for chronic oral consumption. Levels of up to 1,000 µg/day probably offer little risk if limited to days or weeks (Combs and Combs, 1986) and much higher short-term exposure may be acceptable. The fact that some healthy individuals in the areas where selenosis occurs in China may have a daily intake of almost 5 mg of selenium (Yang, et al, 1983) suggests that these recommendations may be conservative.

Westermarck (1977) found no signs of selenium poisoning in patients receiving the equivalent of 1,600 µg/day for a 70 kg male. Dietary protein appears to offer some protection against selenium poisoning (Gortner, 1940). Torula yeast, methionine (if dietary vitamin E is adequate), inorganic sulfur compounds, and other food supplements have also shown varying degrees of protection (Combs and Combs, 1986).

The recommended levels of selenium to prevent deficiency and avoid toxicity problems are presented in Table 3.3. The wide ranges demonstrate the lack of knowledge about selenium. Selenium requirements vary as a result of many factors. Many of these recommendations do not include consideration of the beneficial effects of selenium as offering some protection against cancer and infection.

Table 3.3. Selenium in the Human Diet

Diet intake	Observed effect

µg/day

100,000

--27,000 selenium toxicosis from errors in food supplement production

10,000

Adverse affects from too much selenium

--5,000 healthy individuals in areas in China where selenosis occurs
--2,400-3,000 long-term exposure borderline for toxic chronic selenosis (Wilber, 1980)

--2,000 no reported problems in people taking supplements (McCarty, 1984)
--1,600 no observed problems in patients treated with selenium for disease
--1,000-1,500 maximum tolerable level (Koller and Exon, 1986)

1,000

-- 775 maximum rec. long-term intake (Combs and Combs, 1986)
-- 500 long term (Sakurai and Tsuchiya, 1975)
-- 250-300 rec. max. (Schrauzer and White, 1978)
-- 200-350 recommended (Passwater, 1980)
-- 210 EPA acceptable daily intake
-- 200 National Research Council recommended range
-- 176 Range of U.S Daily diet, general population
-- 130 average of ten California residents (Schrauzer and White, 1978)

100

-- 90 minimum requirement (Koller and Exon, 1986)
-- 66-70 Selenium balance studies, U.S.
-- 60 Range of U.S Daily diet, general population
-- 50 National Research Council recommended range
-- 28-32 apparently adequate in New Zealand and China
-- 20 selenium balance study, New Zealand
-- 16-20 apparent protection from Keshan disease in China

10

Adverse effects from too little selenium

Keshan disease and other deficiency problems

Sources: Sakurai and Tsuchiya, 1975; Schrauzer and White, 1978; NRC, 1980; Passwater, 1980; Levander, 1982; McCarty, 1984; Combs and Combs, 1986; Koller and Exon, 1986; Coppock, 1987.

Lafond and Calabrese (1979) stated that current biomedical and epidemiological findings justified raising the drinking water standard from 10 µg/L to 50 µg/L. The apparent lack of adverse effects from exposure to much higher levels of selenium in drinking water (Valentine, et al., 1978, 1981, and 1987) and the protective action of selenium against cancer, infection, and disease (section C of this chapter) would support this action.

F. Selenium exposure in California

It is unlikely that either clinical selenium deficiency or toxicity will occur in California except in unusual cases, i.e., accidents, such as errors in the preparation of food supplements or interaction between selenium and other materials and drugs in individuals on very restricted diets. There may be risk of exposure for people who are malnourished and eat large amounts of waterfowl and fish (including internal organs) from areas with high selenium levels.

The University of California has completed a number of studies of selenium content of California food crops in the last three years in response to public concern over possible selenium exposure. These included both studies of actual field conditions and laboratory and field studies of selenium-enriched soils. Several crops were found to have elevated selenium concentrations (Table 3.4).

The average daily intake from eating these foods would be low. The vegetables collected from farm fields where high selenium levels would be expected would add only 1-20 µg per day to a typical diet (Fan, 1987). This quantity is less than 10% of the conservative EPA recommended maximum, and even a smaller fraction of the higher allowable level suggested by Combs and Combs (1986) and Koller and Exon (1986).

The groups at greatest risk of selenium over-exposure are those that collect and eat whole fish and wildlife from areas with elevated selenium levels (Table 3.5). Selenium content of organs is higher than in muscles, and consumption of the whole fish rather than eating only the flesh, as is most common in the U.S., would provide a much higher dose of selenium.

The finding of elevated levels of selenium in fish and game in some areas of California led to health advisories in the 1987 Sport Fishing Regulations and Public Health Advisories. For example, these suggest that no one should eat more than 113 gms (4 oz) of corvina, croaker, sargo, and tilapia from the Salton Sea during any two week period. These advisories also apply to fish and wildlife taken from the Grasslands/Kesterson area and Suisun Bay.

These public health advisory recommendations would limit added dietary selenium to less than 484 µg/day with the highest levels of

Table 3.4. Selenium concentrations in and human exposure to agricultural crops in the Western San Joaquin Valley

		Selenium concentration		Selenium exposure		
		Geometric				
Source	Tissue	Mean	Maximum	Average	Highest	Average[d]
		------------ µg/g	------------	------------- µg/serving	--------------	
Bell pepper	Fruit	0.0078	0.0132	0.78	1.32	
Broccoli	Head	0.0530	0.1106	5.30	11.06	
Cabbage	Head	0.0136	0.0281	1.36	2.81	2.2
Cantaloupe	Fruit	0.0128	0.0303	2.05	4.85	0.4
Carrot	Root	0.0407	0.0652	4.07	6.52	2.2
Cauliflower	Head	0.0385	0.0877	3.85	8.77	0.6
Corn	Grain	0.0036	0.0328	0.58	5.25	0.4
Garlic	Root	0.0381	0.0739	3.81	7.39	24.9
Lettuce	Head	0.0023	0.0081	0.23	0.81	0.8
Lima bean	Seed	0.0685	0.0796	6.85	7.96	
Onion	Bulb	0.0070	0.0082	0.70	0.82	1.5
Sugar beet	Root	0.0030	0.0068	0.30	0.68	
Tomato	Fruit	0.0034	0.0072	0.34	0.72	

Source: Klasing and Pilch (1988) from data in Burau, et al. (1988).
Se concentrations all fresh (wet) weight, conversion factors from Pennington and Church (1985).
Exposures are based on typical serving sizes from Pennington and Church (1985) and Watt and Merrill (1975). National averages based on Pennington and Church (1985).

selenium observed in fish, 60 µg/g for common carp from the San Luis Drain (Klasing and Pilch, 1988), assuming 100% bioavailability and absorption. As the wide range of suggested intakes included in Table 3.3 shows, even this worst-case assumption is within the daily range considered acceptable by several authors, although the intake in that one meal is quite high. Using a more realistic bioavailability of 47%, based on tuna, the daily intake averaged over the two weeks would be only about 200 µg/day, well within the accepted levels. With more typical fish selenium concentrations in seleniferous areas, 4 µg/g, and the same availability factor, consumption of 113 gms/day would add only 212 µg/day to the diet.

Pregnant women, children, and individuals on diets that might increase susceptibility to selenium poisoning (low sulfur/low protein) are probably well advised to follow suggested limits for fish consumption, but Japanese fishermen ingested more than 500 µg of selenium/day with no adverse effects (Sakurai and Tsuchiya, 1975).

The ethnic groups that eat the entire fish are commonly following a tradition from their home country. In selenium-deficient areas such as Sechuan, China or the mountains of Laos, this practice would have played an important role in preventing selenium-deficiency diseases. In California, it may place the consumers at increased risk.

Table 3.5. Human exposure from consumption of livestock, fish, and wildlife in the Western San Joaquin Valley.

Source	Tissue	Area	Se exposure Typical range
			µg/serving[a]
Cow	milk	A	3.05-5.59
	liver	A	29.8-35.2
Cottontail rabbit	thigh meat.	K	50-53
	thigh meat.	VWA	2.7-2.9
American coot	breast meat	TLD,STW,LHR,STW, LHR	5.8
Cinnamon teal	breast meat	TLD,STW,LHR	2.8
	liver	TLD,STW,LHR,WF	11.0
Black bullhead	whole	MS	2.5
Bluegill	whole	MS, VW,SJR, SS, HC	4.60
Channel catfish	whole	CD	1.20
	whole	SLD	17.0
	muscle	SJR,SS,MS,CD	0.90
Common carp	whole	SLD	60.0
	whole	AC,HC,SJ,LB,MS,SS, VWA	3.79
Striped bass	whole	LB,MS,SS,VW,MC,SJR,HC	2.35
White catfish	whole	MS,LB	1.30
	muscle	SS,SJR	0.34
Freshwater clam	muscle	SFC,CD,MS,SS,VWA	4.0

Source: adapted from Klasing and Pilch (1988) based on data from the Biological Residue Database and the Selenium Verification Study. Area codes: A, Bordered by Fresno Slough and San Joaquin River on the east, I-5 on the west, Fresno-Kings County line on the south, and San Joaquin County on the north; AC, Agatha Canal; CD, Camp 13 Ditch, GLC, Goose Lake Canal; GWD, Grassland Water District; K, Kesterson Reservoir; LB, Los Banos Creek; LHR, Lost Hills Ranch; MC, Main Canal; MS, Mud Slough; PCX, Poso Creek, Kern Co; SFC, Santa Fe Frade Canal; SJR, San Joaquin River; SLC, San Luis Canal; SLD, San Luis Drain; SS, Salt Slough; STW, Semitropic Water Storage District Ponds; TLD, Tulare Lake Drainage District Ponds; VWA, Volta Wildlife Area; WF, Westfarmers Evaporation Ponds.

[a] Exposures are based on typical serving sizes from Pennington and Church (1985) and Watt and Merrill (1975).

There is also a small risk of selenium exposure for people using private wells or surface water with high selenium levels. Public water supplies are monitored (and have been since the 1970's), but not all private wells have been tested. Exposure from the highest selenium concentrations detected in irrigation well water could add potentially significant levels of selenium with typical water consumption. Intake of 2 L water/day with a concentration of 380 µg/L (found in one agricultural well in Fresno county) would add as much as 760 µg/day to the diet. This, combined with regular dietary intake, would put the individual at the edge of the range of recommended allowable daily exposure, see Table 3.3. However, Valentine, et al. (1981) found that residents of two communities (not in California) drinking water with high selenium levels, 190 and 380 µg/L respectively, had blood selenium levels only slightly higher than a control community with only 1.7 µg/L of selenium in the water. The only significant difference in symptoms between the communities with low and high selenium was a slightly higher frequency of headaches in the area with high selenium levels.

Much less is known about the extent and seriousness of selenium deficiency in residents of California. It appears to be very common in cattle in many areas of the State (see Chapter 4 in this volume and Chapter 3 in Volume 1). Selenium deficiency would most likely develop in people who drink water with very low selenium concentrations and grow and eat food in selenium-deficient soils. This would be most likely occur on the western slope of the Sierra Nevada Mountains and in areas of Northern California.

Infants are at greatest risk of developing selenium deficiency in California as they are throughout the country. The statistics of SIDS occurrence were compared in areas of apparent low and high selenium status (based on occurrence of selenium deficiency in animals and forage, finding of elevated levels of selenium in plants, water, and fish, and geologic formations) for a preliminary review of possible selenium deficiency in infants (Table 3.6).

This suggests there may be a relationship between selenium status and SIDS. However, until controlled studies are done, this is only an intriguing correlation. It may simply reflect differences in ethnicity, age of mother, quality of health care, or random fluctuation.

In California, SIDS occurrence is most common among blacks, 2.61 per 1,000; intermediate in whites, 1.47 per 1,000, less common among Hispanics, 1.18 per 1,000; and least common among Southeast Asians (SIDS database, 1985; Jacober, 1988). Differences in SIDS occurrence in different ethnic groups may reflect geographic, genetic, or cultural differences affecting dietary intake. The statewide average from 1975-1984 was 1.6 per thousand (SIDS database, 1985).

Some selenium deficiency effects might also be observed in areas that rely on drinking water from source areas that are likely to contain very low levels of selenium. Unfortunately, current monitoring programs are simply concerned with toxicity effects and as long as the levels are below the standard, 10 µg/L, no further analysis is done. If the water contains 5 µg/L the daily consumption of two liters of water could provide 10 µg of selenium. In cases where selenium intake in the foods is very low or where smoking and alcohol are reducing selenium levels, intake in the water may make the difference between selenium deficiency and adequate selenium.

The work of Welsh, et al. (1981) suggests that self-selected diets may be deficient even in areas where most people are obtaining sufficient selenium. They found that 17% of the people studied were eating less

Table 3.6. SIDS occurrence

County	1980	1981	1982	1983	1984	1985	1986	80-86
			SIDS cases per 1000 births					
Areas with apparent low selenium levels								
Butte	2.4	0.9	0.9	2.6	1.3	2.1	1.7	1.7
Madera	0	1.5	1.5	1.5	0.7	0.7	2.9	1.3
El Dorado	2.2	1.4	2.0	5.0	3.4	3.3	5.7	3.3
Mendocino	0.8	1.5	0	1.7	2.5	8.3	2.6	2.5
Tulare	2.2	6.4	2.1	0.9	2.5	1.7	2.7	2.6
Areas with apparent high selenium levels								
Imperial	0.4	0.8	0.9	0	1.5	0.9	0.5	0.7
Monterey	1.5	1.0	0.6	0.8	0.8	0.5	1.7	0.8
San Luis Obispo	0.9	0.9	2.0	1.2	1.2	0.4	1.5	1.2
Santa Barbara	0	0.2	1.4	2.0	1.4	0.6	0.8	0.9
Stanislaus	1.2	1.2	0.6	1.0	0.6	0.5	0.2	0.8
Average, low selenium areas								2.3
Average, high selenium areas								0.9

Source: data on SIDS occurrence from SIDS Information Center, 1988. Areas with apparent higher and lower selenium levels based on data from plant and animal surveys and geologic formations--counties with over 1000 births per year.

than 50 µg/day. Thompson, et al. (1975) found that wheat flour was the major source of selenium for composite diets in three cities in Canada. Individuals consuming diets composed primarily of highly processed foods with little whole grains, broccoli, garlic, mushrooms, Brewer's yeast, Brazil nuts, oysters and other seafoods, and organ meats, such as liver and kidneys, would be most likely to be selenium deficient.

Selenium deficiency is also observed in patients on total parenteral nutrition (Zabel, et al., 1978; McKenzie, et al., 1976; Jacobson and Wester, 1977; Levander, 1984; Cohen, et al., 1989) and has also been related to the use of various drugs (Combs and Combs, 1986).

Both alcohol consumption and smoking have also been linked to reduced selenium levels, and smokers and drinkers are more likely to be selenium deficient (Ellis, et al., 1984). A low dietary intake of selenium, compounded by smoking, alcohol, and possible interactions with other trace elements and high intake of saturated fats, could lead to selenium deficiency even with a dietary level of selenium that would otherwise be considered adequate. Vegetatarians should also pay careful attention to selenium content of foods to ensure an adequate intake. People in these risk groups might wish to increase dietary intake of selenium-rich foods.

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Chapter IV. Selenium in Wetland and Aquatic Ecosystems

Selenium-related reproductive problems in aquatic birds have been observed only at Kesterson Reservoir; however, similar problems may now exist over a much wider area which could expand markedly in the future. In the San Joaquin Valley there are more than 5,300 hectares of drainwater ponds like those at Kesterson, and nearly 28,000 hectares will be needed...

Ohlendorf, et al. 1986b

A. Introduction

Selenium toxicity has been observed in wetlands and aquatic systems in California, and has been the focus of much of the recent research (Ohlendorf, 1985; Saiki, 1985, 1986; Ohlendorf, et al., 1986a,b,c; 1987a,b, 1988). Recent studies in North Carolina have also identified a number of consequences of excess selenium in aquatic ecosystems (Lemly, 1985a). Adverse impacts on fish and wetland birds have been the primary problems. Possible impacts on rare and endangered species are also of concern in California.

The most widely publicized selenium problems in California have been the effects of high levels of selenium on wetland and aquatic ecosystems. Bioconcentration (by living organisms) and biomagnification (the rapid increase in concentration through successive steps in the food chain) can cause problems even when ambient selenium levels in water are relatively low.

Saiki (1985) found that bioconcentration and biomagnification could increase selenium levels more than 1,000 fold from water to fish and animals. Schuler (1987) found that selenium concentrations in sediment were 155 times those in water, those in submerged vegetation were 1,308 times those in water, and those in emergent vegetation were 921 times those in water.

Biomagnification of selenium in the food chain may be a factor of 2-6 per step in the food chain (Ohlendorf, in press). This is corroborated in the bioaccumulation studies in scoters and scaup in Suisun Bay (White, et al., 1988). However, the concentration in special tissues may be many times higher and cycling and recycling can lead to tissue concentrations that are a few hundred to tens of thousands of times higher than the water concentration (Lemly, 1985a; White, et al., 1988), Table 4.1. As a result selenium concentration in water needs to be kept at very low levels to avoid harmful effects in wetland and aquatic ecosystems.

B. Selenium in wetland ecosystems

Wetlands are complex ecosystems that act as filters (which collect material from water that is passing through), sinks (which collect trace elements, such as selenium), and transformers that convert selenium from available forms to the more immobile elemental selenium or to volatile forms such as dimethylselenide. As environmental conditions fluctuate in response to the seasons, changes in ground water and surface water, human and natural activities, and fire, the wetland can

Table 4.1. Bioconcentration factors for selenium in freshwater organisms following exposure to combined waterborne and dietary sources under natural conditions[1]

Organisms	Bioconcentration factor
Fishes	
Carnivores	590-35,675
Planktivores	445-27,000
Omnivores	364-23,000
Benthos	
Insects	371-5200
Annelids	770-1320
Crustaceans	420-1975
Molluscs	600-2550
Plankton	
Zooplankton	176-2080
Phytoplankton	237-1320
Periphyton[2]	158-1070
Plant[3]	166-24,400
Birds[4]	
Waterfowl	190-3750
Marsh birds	300-3850

[1] Concentration present in tissues (µg/g wet weight) divided by the mean waterborne concentration (µg/L). Largest numbers for fishes represent maximum bioconcentration observed in visceral tissues (spleen, heart, kidney, pancreas, gonad); smallest numbers for fishes represent low bioconcentration factors for skeletal muscle

[2] Attached diatoms and filamentous algae

[3] Rooted macrophytes; roots, stems, leaves, seeds

[4] Migratory species

Source: Lemly, 1985a

also become a source of selenium for areas downstream or downwind. Wetlands are very productive and can approach or surpass agricultural fields in primary productivity (Mitsch and Gosselink, 1986). For example, a freshwater swamp may have a mean primary productivity of 2,000 g/m^2/yr (Lieth and Whittaker, 1975). This high biological activity makes biological cycling a key part of elemental distribution.

Understanding the various processes and their interactions in wetland ecosystems is essential for determining the best management strategy for California wetlands affected by selenium. Unfortunately, research in California wetlands has been limited. While recent studies have provided some insight about the behavior of selenium in two California wetlands, Kesterson Reservoir and the Grasslands, little is known about the specific structure and function of these wetland ecosystems. Studies of elemental cycling in wetlands in other states have been used to evaluate how selenium may behave in California wetlands (see for example, Richardson, et al., 1978). More detailed, long-term studies are needed of California wetlands structure and function.

Wetlands have been used in water treatment and for treating urban runoff for many years (Brown, 1984; Richardson and Nichols, 1985). Brown (1984) found that a cattail marsh retained 97 percent of the non-volatile suspended solids. As wetlands capture these sediments, they also collect toxic materials and heavy metals adsorbed on them (Boto and Patrick, 1979).

The wetlands of the Grasslands area have been studied to a limited degree (State Water Resources Control Board Technical Committee, 1987). In addition, analysis of the pattern of selenium concentration at Kesterson Reservoir provided some insight into the retention pattern of selenium in California wetlands (USDI, 1984, and 1986). These studies revealed that both Kesterson Reservoir and the Grasslands were excellent sinks for selenium in drainage water. When the Grasslands area was bypassed, the selenium load was rerouted to the San Joaquin River and selenium inputs to the river increased from 1,176 kg/year to 3,513 kg/year (Bontadelli, 1985).

The nutrients that are trapped in the wetland are primarily stored in the peat/litter compartment rather than in the water or the plants (Verhoeven, 1986). Very little is known about selenium retention and release in wetlands. The few small studies of sulfur (in many respects an ecological analog of selenium) that have been performed, show relatively high retention of sulfur, up to 73 percent when the wetland remained anaerobic (Hemond, 1980; Weider and Lang, 1984; Bayley et al., 1986; Urban, et al., 1986). However, when the wetland dries out and becomes aerobic, it becomes a source of sulfur for downstream areas (Richardson, 1988). Weres, et al. (1985) provided evidence of similar behavior of selenium in the wetlands at Kesterson Reservoir. His group has found that selenium is relatively immobile if anaerobic reducing conditions are maintained, but is mobilized when the system becomes aerobic. Wetting and drying produces both conditions in seasonal wetlands. Management of water levels to maintain permanent wetlands may reduce the selenium risk to wildlife by sequestering selenium in anaerobic sediments.

1. Selenium in wetland plants
   In a study of plants in a wetland with selenium input from coal flyash, *Typha latifolia* (cattail rush) had the highest selenium levels (Guthrie and Cherry, 1979). Distribution of selenium in wetland plants is not well known. Cherry and Guthrie (1979) compared selenium partitioning in sedge grass (*Andropogon virginicus*) and nutgrass (*Cyperus retrofractus*). In both species, the roots and leaves had the highest selenium concentrations. Estabrook, et al. (1985) found selenium concentration in cattail (*Typha latifolia*) was highest in old fruits, almost 2 1/2 times as high as in roots and leaves. Schuler (1987) also reviewed selenium distribution in cattails. Saiki (1985) found selenium concentrations of up to 390 µg/g dry weight in rooted plants at Kesterson Reservoir.

2. Wetland birds as a special concern
   Reproductive problems of birds nesting in wetlands with high selenium levels were noted in 1983, with few signs of adverse effects in adult birds (Ohlendorf, et al., 1984; 1986a; Ohlendorf, 1985). Surveys of selenium levels in birds subsequently determined that the selenium content of bird livers at Kesterson Reservoir reached 360 µg/g (dry weight), as shown in Table 4.2 (Ohlendorf, 1985; Ohlendorf, et al., 1986a, 1987a; Saiki, 1985; Presser and Ohlendorf, 1987).

   The selenium concentrations in average or normal birds are not known, but those from Humboldt Bay may be lower than average since the watershed is apparently low in selenium (see Chapter 5). For further data from field studies of selenium concentrations in birds see: Koranda, et al., 1979; U.S. Dept. of Interior Task Group, 1985; Ohlendorf, et al., 1986a,b; Ohlendorf, et al., 1987; Ohlendorf, et al., 1988; Presser and Ohlendorf, 1987.

   Relatively little research has been done on the effects of selenium deficiency and excess selenium in wild birds, game species and, perhaps most critically, on rare and endangered species. Some field and lab research on the effects of selenium on avian reproduction has been completed recently (Ohlendorf, et al., 1986a,b,c; Ohlendorf, et al., 1987a; Ohlendorf, in press; Heinz, et al., 1987; 1988) but limited research funding has often restricted these studies to analysis of total selenium, rather than the more important question of the effects of different selenium compounds and possible dietary interactions (Ohlendorf, 1987b).

   Eleven of twelve mallards fed 100 µg/g selenium as sodium selenite for a study on reproduction, approximately the food source concentration at Kesterson Reservoir, died before the study was completed (Heinz, et al., 1987). Ten µg/g selenium as selenomethionine affected mallard reproduction more severely than the same concentration of sodium selenite. The selenite was embryotoxic while the selenomethionine was more teratogenic.

Table 4.2. Selenium concentrations in tissues of California birds

Sample	Site	Selenium (dry weight) range	mean
		µg/g	µg/g
Coot livers	Kesterson Reservoir[1]	19-360	81.5
	South Grasslands[1]	17-30	23.3
	North Grasslands[1]	7.0-28	12.9
	Suisun Bay[2]	3.2-19.6	7.4
	Volta Wildlife Area[1]	1.8-14	5.4
Stilt livers	Kesterson Reservoir[1]	19-80	46.4
	South Grasslands[1]	9.7-53	35.6
	North Grasslands[1]	4.3-41	12.7
	Volta Wildlife Area[1]	6.3-9.9	7.8
Surf scoter livers	San Pablo Bay[2]	42.9-196.4	118.1
	Suisun Bay[2]	13.1-136.7	73.5
	Morro Bay[2]	12.3--35.7	23.9
	Humboldt Bay[2]	6.4-28.0	15.2
Surf scoter flesh	San Pablo Bay[2]	5.6-32.9	15.0
	Suisun Bay[2]	6.4-21.8	12.1
	Morro Bay[2]	2.2-6.4	4.2
	Humboldt[2]	1.6-6.4	3.1
Canvas back flesh	San Pablo Bay[2]	0.7-10.0	4.3
Canvas back liver	San Pablo Bay[2]	8.1-26.1	14.2

Sources: [1]Ohlendorf, et al., 1987a; [2]White, et al., 1988.

Adult mallards fed 8 µg/g produced fewer deformities, still ten times the control rate, but many of the ducklings died within three days. Female mallards fed 16 µg/g selenomethionine failed to produce any surviving young while selenocysteine at the same concentration did not impair reproduction (Heinz, et al., unpub). Studies with other birds, including chickens, quail, and mallards, suggest that problems become apparent at dietary levels of 7 µg/g (Ohlendorf, in press). Analysis of field data on reproductive success of coots, stilts, and grebes suggested some differences in selenium exposure or tolerance (Ohlendorf, et al., 1986a,b).

Coots in the selenium contaminated Kesterson Reservoir in 1983 lost nine times more eggs to embryonic mortality than would normally be expected (Ohlendorf, et al., 1986b). Subsequent studies revealed similar concentrations in the Grasslands waterfowl area with duck and avocet eggs containing almost 7 µg/g selenium and liver selenium concentrations up to 85 µg/g dry weight. U.S. Fish and Wildlife Service (unpub.) diagnosed selenium toxicosis as a cause of death in a number of birds at Kesterson Reservoir and found the following liver dry weight selenium levels: ruddy duck--110 µg/g, rail--20 µg/g, hawk--76 µg/g.

Studies of domestic birds have provided much of the information on the possible impacts of elevated selenium levels on waterfowl. Chronic toxicity in chickens resulted from levels of 7-8 µg/g dietary selenium dry weight (Ohlendorf, 1985, in press). Poley and Moxon (1938) showed that dietary selenium at 5 µg/g depressed chicken egg hatch and survival and at 10 µg/g there was total failure. Low hatch rates for eggs have been used to locate potentially seleniferous areas (Rosenfeld and Beath, 1964). The eggs may be fertile but include gross deformities such as missing eyes and beaks and distorted wings and legs (Franke and Tully, 1935; Franke, et al., 1936; Carlson, et al., 1951; Gruenwald, 1958). Selenium may reduce survival as a result of induced anemia even when chicks appear normal (Kury, et al., 1967). There is also evidence that subclinical exposure may depress immune system response and lead to death from secondary infection.

The selenium concentrations in different species of birds appear to be a function of the period of residence and consistency of feeding within the contaminated areas. Resident populations are most affected but transients and migratory species in the Pacific Flyway may also be affected by the high levels of selenium in some areas of California, notably the Salton Sea and Central Valley (Ohlendorf, 1987; Ohlendorf, et al., 1987a,b). Selenium toxicosis has been diagnosed as the cause of death of many coots as well as smaller numbers of waterfowl, raptors, and fish-eating birds at Kesterson National Wildlife Refuge (Ohlendorf, in press; Ohlendorf, et al., 1988; U.S. Fish and Wildlife Service, unpub.). The magnitude of reproductive problems statewide is not known. Recent studies have shown deformities similar to those found at Kesterson Reservoir in the Tulare Basin (Skorupa and Ohlendorf, 1988); and the mean concentrations of selenium in duck livers in some parts of the San Francisco Bay complex approach those of selenium-poisoned birds at Kesterson Reservoir. More extensive surveys and more detailed research will be needed to determine the scope of the problem statewide and the importance of selenium toxicosis compared to other environmental contaminants and habitat loss.

Although the emphasis has been placed on the adverse effects of selenium on wetland birds, it is also possible that some birds will benefit from increased selenium uptake. Combs and Peterson

(1983), for example, found that increased selenium (0.10 µg/g sodium selenite in the diet) tripled the LD_{50} for paraquat in chicks. With the relatively high levels of pesticides found in fish in some areas of the Central Valley (Agee, 1986; Linn, et al., 1986), adequate or slightly elevated selenium levels might provide some protective benefits.

Some migratory birds may also benefit from the higher selenium levels in California. Birds that spend the summer in northern Canada and Alaska in areas with low ambient selenium levels (Ullrey, 1981) increase their selenium levels while they winter in California. This could provide benefits during the subsequent breeding season in the north. This increase in selenium concentration is confirmed by the data in White, et al. (1988), which shows that selenium levels in scoter muscles (*Melanitta perspicillata*) increased 150% in San Pablo Bay from November to March. The selenium concentrations in scoter muscles increased 30-50% and even larger increases were seen in scaup (*Aythya spp.*).

C. Selenium in aquatic ecosystems

Selenium behavior in aquatic ecosystems is similar to the behavior of selenium in wetlands. Over time, selenium in an undisturbed system appears to be concentrated in the upper layer of the sediment (Lemly and Smith, 1987). However, roots, bottom feeders (particularly invertebrates), and microbes can mobilize selenium and move it to the surrounding environment. Selenium may also be mobilized as the roots die back in winter or as a result of drying in the summer which results in aerobic soil conditions.

1. Selenium in aquatic vegetation

Aquatic plants include algae, mosses, ferns, and flowering plants. They exhibit four types of growth habit, floating (unattached), floating (attached), submerged, and emergent plants (Cook, 1974). Little is known about the uptake and accumulation of elements in aquatic plants. Nutrient absorption can occur both through leaves and the typically poorly developed roots. The uptake of selenium probably depends on species cation-selection ability, salinity, pH, alkalinity, growth rate, and oxygen concentration.

Algae can bioconcentrate selenium several thousand times (Foe and Knight, 1986). Algae in a pond contaminated with selenium from coal flyash had 0.6 µg/g selenium dry weight (Furr, et al., 1979). Birkner (1978) found selenium concentrations in pond algae up to 21.0 µg/g dry weight in a seleniferous area in Colorado. Saiki (1986) found selenium concentrations in algae ranged from 12.0-330.0 µg/g dry weight with a mean of 68.6 µg/g at Kesterson Reservoir, but a mean selenium concentration of only 0.5 µg/g at the Volta Wildlife Area. Algae actively absorb selenium and employ it as a sulfur analog (Shrift, 1954; Wrench, 1978).

Relatively few studies on trace element uptake in aquatic plants have tested for selenium. Saiki (1986) and Saiki and Lowe (1987) found submerged, rooted plants contained from 18-390 µg/g selenium dry weight, (mean 73.0 µg/g) at Kesterson Reservoir.

2. Selenium in aquatic insects
   Selenium content of insects ranged up to 330 µg/g dry weight at Kesterson Reservoir and 326 µg/g at the San Luis Drain (Saiki, 1985, 1986; Saiki and Lowe, 1987). One aquatic species, Waterboatmen (*Corixidae*), contained 30-100 µg/g selenium dry weight at the Westfarmers evaporation pond in the Tulare Lake Basin (Schroeder and Palawski, 1987; Schroeder, et al., 1988). Bottom-dwelling invertebrates at Grassland Water District averaged 6.9 µg/g dry weight but ranged as high as 22 µg/g while free-swimming invertebrates averaged 6.2 µg/g and ranged as high as 60 µg/g (San Joaquin Valley Drainage Program, 1987).

3. Selenium in fish
   Effects of selenium on fish have been summarized by Lemly (1987). Selenium is an essential nutrient for fish but can also be toxic. Elevated selenium levels in water or diet can lead to a variety of pathological symptoms, reproductive failure, and death. The symptoms of selenium exposure include edema (Sorensen and Bauer, 1984; Sorensen, et al., 1984; Finley, 1985); cellular distortion, including changes in the blood (Sorensen and Bauer, 1983; Finley, 1985); necrosis and rupture of the egg follicles in the ovary (Sorensen, et al., 1984). Spinal and skeletal deformities are seen in progeny of fish that are able to reproduce with high selenium exposure (Lemly, 1987). Most deformities are lethal before growout.

   Selenium exposure has also been shown to reduce the temperature tolerance of fathead minnows (Watenpaugh and Beitinger, 1985). This may be an important factor for other species of fish in the warmer areas of California where selenium is a problem. The removal of riparian trees results in considerably higher water temperatures in the summer. Many of the waterways affected by selenium in the San Joaquin Valley have had riparian vegetation removed as a result of agricultural practices. Anderson (1973), summarizing a number of studies on tree removal and stream temperature, reported that tree removal could increase water temperature as much as 13°C (24°F). This can be critical for game species, e.g., trout and salmon, that require lower temperatures. For example, the maximum upper lethal temperature for Pacific salmon is 25°C (77°F) (Brett, 1952). Increased temperatures can alter species distribution and may accentuate the toxicity of trace elements and pesticides.

   Fish sampled nationwide averaged about 0.5 µg/g whole body wet weight, or about 2.0 µg/g dry weight (Ohlendorf, in press). The range within California fish varies from <1 µg/g to more than 430 µg/g dry weight but is generally within acceptable limits in game fish. Some of the higher levels are presented in Table 4.3. Trout with liver selenium levels of 9.1 µg/g did not have measurable selenium in the flesh (Agee, et al., 1985), demonstrating the marked ability of the liver to concentrate and store selenium.

Selenium toxicity in fish is affected by many factors including age, life stage, sex, nutritional status, health, form of exposure, concentration, and duration of exposure (Lemly, 1985a). Water conditions such as hardness, temperature, and suspended solids may also be important. There is also considerable variation in tolerance between different species (Lemly, 1985b; see also Volume 1, Chapter 3). Accurate predictions of the risk of selenium toxicity is difficult because these factors, and more critically, their interactions, are poorly understood. This may be important because of the occurrence of high concentrations of elements such as arsenic, boron, other trace elements, and many types of pesticides in California's aquatic ecosystems, especially those receiving surface and subsurface agricultural drainage (Agee, 1986; Linn, et al., 1986; Bradford, 1988). For example, Linn, et al. (1986) found 11 pesticides and PCBs in a channel catfish from the San Joaquin River. A carp from the Alamo River contained 20 pesticides, with almost 7 µg/g of both DDT and DDE.

Table 4.3. Elevated selenium concentrations observed in California fish

Fish tissue and species	Site collected	Average tissue concentration
		µg/g (dry weight)
Mosquitofish whole	Kesterson	16.0-430.0
Mosquitofish whole	Grasslands	5.2-18
Green sunfish liver	Grasslands	5.5
Rainbow trout liver	McCloud River	6.5-9.1
Brown trout liver	Hot Creek	5.1
Sargo liver	Salton Sea (South)	5.6
Croaker liver	Salton Sea (South)	6.2
Zill's cichlid liver	Salt Creek Slough	17.0
Striped mullet	Tijuana Slough	3.2-6.1
Largemouth bass	San Antonio Reservoir	4.5-5.5

Sources: White, et al., 1988; Saiki, 1985; Ohlendorf, et al., in press; Agee,1986; Greenberg and Kopec, 1985. (See Volume 1, Chapter 3 for a more complete list.)

Selenium pollution of lakes from coal-fired power plants flyash effluent in North Carolina has provided considerable information on the effects of selenium on fish. Selenium levels of 10-20 µg/L in the reservoir eliminated 16 of the 20 original fish species of fish in one cooling reservoir (Lemly, 1985b). Two of the surviving species were sterile (with adults persisting), one species recolonized from elsewhere as sterile adults, and only one was seemingly unaffected (Lemly, 1985b). These results indicate the potential adverse impact of selenium-rich agricultural drainage; but, differences between North Carolina and California environments, overall composition of the water, fish species, and food chains make only rough comparisons possible. Other investigators have reported toxicity problems when selenium levels in water reached 40-53 µg/L (Hodson, et al., 1980). A diet of mayfly nymphs containing 14 µg/g dry weight selenium killed 3 of 4 bluegills tested (Finley, 1985).

The following results have been reported from laboratory studies of some key California fish species. Selenium levels as low as 6.5 µg/g dry weight in food reduced survival and growth of chinook salmon fry and fingerlings. Some adverse effects were observed when chinook salmon and fingerlings were fed selenium concentrations as low as 3.2 µg/g dry weight (Hamilton, et al., 1987; Palmisano, 1987). Selenium also impeded the osmoregulatory ability of fish and reduced migratory behavior (Palmisano, 1987). Selenium exposure reduced salmon's ability to meet the challenge of adjusting to salt water, with more than a 50 percent reduction in survival with 26 µg/g Se in the diet (Hamilton, et al., 1987).

Hilton, et al. (1980) reported reduced growth of trout fed 13 µg/g sodium selenite. They suggested that long-term exposure to 3 µg/g dry weight sodium selenite in the diet might be toxic.

Mosquitofish appear to have a high tolerance for selenium and were the only fish species found in Kesterson Reservoir and the predominant fish in the San Luis Drain (USDI, 1986). Mosquitofish are collected for selenium monitoring. Their survival in high selenium water could produce high selenium levels in predators that consume them.

Selenium deficiency in fish may also occur but has been little studied in natural ecosystems. Bell, et al. (1986) found that rainbow trout developed selenium deficiency problems when the food source contained 0.025 µg/g dry weight selenium. Ataxia, inability to coordinate voluntary movement, occurred in about 10 percent of the selenium deficient trout and both liver and nerve abnormalities were observed. A level of 1.0 µg/g selenium dry weight in the diet appeared sufficient for nutritional requirements. Gatlin and Wilson (1984) found the minimum selenium requirement of catfish was 0.25 µg/g (dry diet).

4. Selenium in shellfish

Shellfish serve as effective filters and can serve as indicator organisms for trace elements and other chemicals in water. As a result, State agencies rely on data from shellfish, especially mussels, in the State Mussel Watch Program. Selenium levels in excess of the International Standard (0.3 µg/g) were detected at several sample stations in 1985-86 (Hayes and Phillips, 1986).

The selenium verification study in 1987 confirmed the probable impact of selenium discharges from oil refineries in the San Francisco Bay area (White, et al., 1988). Mussels (*Mytilus californianus*) contained 2.28 µg/g wet weight selenium near Rodeo (UNOCAL refinery outfall) and 3.03 µg/g near Richmond (CHEVRON refinery outfall). Selenium concentration had increased 330-470 percent during the winter after the test organisms were set out. Rapid increases in oyster selenium concentration were also observed in the Carquinez Strait (SHELL refinery outfall).

D. Summary

Selenium contamination of wetlands and aquatic systems can have significant impacts on fish and wildlife. Reproductive effects may be the first sign of selenium contamination (Lemly and Smith, 1987). As concentrations increase, effects are more likely to cause increased or total mortality of young and adults. Field and laboratory studies suggest that bioconcentration can lead to problems with only 2 to 5 µg/L in water. Food concentrations of 3-8 µg/g dry weight appear to represent levels that can cause toxic effects in fish and wildlife.

Permanent wetlands act as sinks for selenium and may suffer relatively little disturbance from selenium input in the short term, if undisturbed. However, a balance between input and output of a permanent wetland would eventually be expected. Seasonal wetlands are more likely to result in selenium problems. Careful management of wetland and aquatic systems can minimize problems of selenium mobilization. Natural processes of volatilization, burial, and flushing may result in a gradual cleanup of an area, once additional inputs are eliminated.

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Chapter V. Selenium Deficiency and Toxicity in Livestock, Poulty, and Wildlife

The very low selenium area....extends into northern California. Essentially all of the hay and forage produced in that area contains too little selenium to protect livestock from white muscle disease.

Carter, et al. 1960

A. Introduction

Both selenium deficiency and toxicity have been observed in livestock and poultry (NRC, 1976) and wildlife (Herbert, et al., 1971; Ohlendorf, et al., 1986a,b). In California, selenium deficiency is much more common than selenium toxicosis. Selenium deficiency may occur when soils are low in selenium, selenium availability in soils is limited, or when plants with inherently low selenium uptake are grown. Selenium deficiency may also occur when vitamin E is deficient or when mineral imbalances develop (Johnson, 1988). Selenium toxicity in animals is very uncommon and occurs primarily in areas with high concentrations of available selenium in the soil. Selenium toxicity in birds and wildlife is also apparently rare, but does occur as a result of bioconcentration and biomagnification in wetland or aquatic ecosystems (see Chapter 4).

B. The selenium cycle in terrestrial ecosystems

Selenium is widely distributed in soils but its concentration is usually low, averaging between 0.2 and 0.4 µg/g on a worldwide basis (Wiggett and Alfors, 1986). Igneous rocks are often inherently low in selenium and are the parent material of many selenium-deficient soils (Sharman, 1960; Kubota, et al., 1967; Gardiner 1969; Johnson, 1974). The selenium cycle in terrestrial ecosystems is complex and not well understood (Allaway, et al., 1967). It involves the soil structure and soil chemistry; microorganisms, including bacteria and fungi; plants; animals; water; and the atmosphere (Ullrey, 1981; Gissell-Nielsen, 1984; Gissel-Nielsen, et al., 1984). Microorganisms appear to play a very important role in selenium cycling by changing the selenium form (solid-gas), chemical state (inert-active), and by making it less or more available to plants (Volume 1, Chapter 3).

Plant uptake varies a great deal between species and between varieties. Many plants have been found to have elevated selenium concentrations including the following: *Astragalus, Atriplex, Grindelia, Grayia, Stanleya,* Alkali bullrush (*Scirpus),* Cattails *(Typha*), Wheatgrass (*Agropyron)*, Indian Ricegrass (*Oryzopsis hymenoides*), Sunflower (*Helianthus sp),* wild mustard (*Brassica kaber* D.C.), Birdsfoot trefoil (*Lotus corniculatus* L.), Dandelion (*Taraxacum officinale* Weber), Narrowleaf plantain (*Plantago lanceolota* L.), Wild carrot (*Danucus carrota* L.), Yellow rocket (*Barbarea vulgaris* R. Br.), and Lambsquarters (*Chenopodium album* L.); *Asters*, including *A. adsurgens* Greene, *A. Adscendens* Lindl., *A. campestris* Nutt, *A cummutatis* T. and G., and *A. ericoides* (Nutt) *A. (Xylorhizza) orcutti* Vasey, and *A. wrightii* Gray and *Machaeranthera* (Hamilton and Beath, 1963a,b; Beath, et al., 1934, 1937, 1941; Moxon, 1937; Carlisle and Cleveland, 1958; Ehlig, et al., 1960; Kingsbury, 1964; Izbicki and Harms, 1986).

Studies with radioactive ^{75}Se showed that the following species may also accumulate more selenium than average plants: Kentucky tall fescue (*Festuca arundinacea* Schreb.), Bermuda grass, Crested wheatgrass (*Agropyron desertorium* Fisch) var. Nordan, Quackgrass, Wild carrot, Yellow rocket, Sulfur cinquefoil (*Potentilla recta* L), and Lambsquarters (Ehlig, et al., 1960). Range grasses growing in seleniferous areas were studied by Moxon (1937) and Olson, et al. (1942). They found western wheat grass, *Agropyron smithii,* was the most effective selenium accumulator of the grasses they studied.

Among crop plants, turnip, cress, and cabbage (Fleming, 1962), onion, mustard (Lakin, 1972); turnip greens (Yang, et al., 1983); sunflower, rape, oats, wheat (Hamilton and Beath 1963b); broccoli, cotton, and cauliflower (Burau, et al., 1987) have been found to have higher than average concentrations of selenium. The Cruciferae have generally been found to contain higher concentrations of selenium compared with other plants when sampled over a range of soil types (Hamilton and Beath,1964). Bisberg and Gissel-Nielsen (1969) found the following decreasing plant selenium concentrations on low-selenium soils: crucifers > rye grass > legumes > cereals. This trend was unchanged by variations in soil-selenium concentrations and selenium oxidation states. Mushrooms, especially *Boletus and Agaricus,* are also effective selenium accumulators (Piepponen, et al., 1983; Quinche, 1979).

Marked differences in selenium concentration were also found in several species in New Zealand (Davies and Watkinson, 1966). Grasses accumulated two to four times more selenium than white clover (*Trifolium repens* L.), with *Agrostits tennis* consistently showing the highest concentration. This latter species also accumulated more selenium in pot experiments than either ryegrass (*Lolium perenne*) or red clover (*T. picatense*) (Peterson and Butler, 1966; Walker, 1971; Godwin, 1968).

Substantial differences have also been reported between different varieties of a species. Selenium concentration between different varieties of soybeans varied 600% when grown on the same soils in Iowa (Wauchope, 1978). Similar variations were found in 12 varieties grown in Mississippi (Wauchope, 1978). Groce (1972) found a three-fold range in corn selenium concentration between different varieties.

Plants most commonly found with very high levels of selenium are species of *Astragalus* and *Stanleya* as first discovered by Beath, et al. (1934). Not all members of the Astragali are accumulators. Some are excellent forage plants, and others have high levels of alkaloids which can be toxic. Some species require seleniferous soil for successful growth. In soils containing 20 μg/g in the surface 0.3 m, some native range grasses had selenium concentrations of 47 µg/g while the accumulators *A. bisulcatus* and *A. pectinatus* reached 2,590 µg/g and 860 µg/g respectively (Beath, et al., 1939). Beath, et al. (1941) found *A. bisulcatus* with 1,468 µg/g and *A. pectinatus* with 1,375 µg/g growing next to wheat with only 1.9 µg/g. The highest plant tissue concentration of selenium recorded under field conditions was 15,000 µg/g in *Astragalus racemosus* (Beath, et al., 1937).

C. Selenium as an essential nutrient for livestock, poultry, and wildlife

If soil selenium levels or selenium availability is low, then forages may be selenium-deficient and livestock grazed or fed these plant materials must be given selenium supplements. Selenium deficiencies in animals and birds result in substantial economic losses in production in many countries of the world (Allaway, et al., 1967; Kubota, et al., 1967; Lakin, 1973; NRC, 1976; Jenkins and Hidiroglou, 1972; Bisbjerg and Gissel-Nielsen, 1969). Selenium deficiency is relatively common in livestock in California (Carter, et al., 1960; Williams, 1980; Norman, 1987) and recent studies suggest selenium deficiency may also be important in game mammals (Fleuck, 1988; Smith, 1987). Populations of non-game wildlife may also be affected by selenium deficiency. There are very few well-documented reports of selenium toxicity or deficiency in wildlife, other than aquatic birds (see Chapter 4), but this may be largely due to lack of study.

Selenium deficiency diseases in animals were identified in the 1950's (Schwarz and Foltz, 1957). The initial discovery of the nutritional requirement for selenium has been followed by many others, but the understanding of selenium and its many roles in animal nutrition is still limited. Research in this area is complicated by the interactions between selenium, vitamins, proteins, sulfur, and other elements and compounds (see also Chapter 3, 4 and Volume 1, Chapter 3.)

White muscle disease of lambs was the first selenium deficiency disease of animals clearly identified and treated (Muth, et al., 1958). White muscle disease (nutritional muscular dystrophy) is a common outcome of selenium deficiency (Andrews, et al., 1968; Hartley and Grant, 1961; NRC, 1976; Underwood, 1977). Animals with white muscle disease develop chalky white striations, degeneration, and necrosis in cardiac and skeletal muscles. Heart failure, paralysis (usually of the hind legs), a dystrophic tongue, and elevated serum glutamic oxalacetic transaminase values may be evident (Andrews, et al., 1968).

Many other selenium deficiency related effects in animals have been identified or suggested, including: ill-thrift, edema, peridontal (gum) disease, mastitis, retained placenta, dysentery, sudden death, scouring, hepatic necrosis, muscular dystrophy, hemorrhagic ileitis, and ecchymotic hemorrhages (NRC, 1976; Williams, et al., 1982; Shamberger, 1983; Smith, et al., 1985; Combs and Combs, 1986; Plant, 1988).The inclusion of supplemental selenium in the diet has substantially decreased the incidence of retained placenta in cows in some cases (Julien, et al., 1976). Animals have been shown to respond positively to selenium supplements for prevention or treatment of selenium deficiency diseases (NRC, 1976).

Selenium supplementation has also been shown to improve immune system response in animals. Supplementing a basal diet (0.068 μg/g) for weaned pigs with 0.9 μg/g selenium produced the highest antibody response (Blodgett, et al., 1986). Studies have also shown that adequate selenium in the mothers diet may improve birth, survival, and growth rates (Robinson, 1986).

Chronically infertile ewes responded to selenium supplementation, with only 2.5-4% staying infertile compared with 30% of those untreated, and lambing percentage increased to 85.7% compared to 52.2% for controls (Combs and Combs, 1986). Infertility of mice due to selenium deficiency has also been observed (Combs and Combs, 1986). A correlation of selenium deficiency with ill-thrift in cattle was found in northern California (Williams, et al., 1982).

Changes in pasture management have been correlated with the emergence of selenium deficiency in animals (Muth, 1955; Ewan, et al., 1968). Selenium decreases have been attributed to a change to more intensive production methods and increased fertilizer use, which can lead to larger plants with lower selenium concentrations, i.e., the dilution effect (NRC, 1976; Jarrell and Beverly, 1981; Williams, et al., 1982). Other possible contributing factors include leaching of selenium by irrigation water, decreased availability of selenium as a result of intense cultivation and fertilizer use, the effect of long-term harvest and removal, competition between different ions in the soil resulting from changes in soil chemistry related to fertilization and cultural practices, the effect of acid rain and air pollutants, and the effect of fertilizers, chemical controls, and pollutants on soil microorganisms (Brown and Carter, 1969; Carter et al., 1960; Kubota and Allaway, 1972; Frost, 1984; Gissel-Nielsen, 1984).

Sulfate may reduce selenium uptake in plants, possibly due to a competitive effect between the structurally similar selenate and sulfate ions (Pratley and McFarlane, 1974; Jones, et al., in press). Phosphates generally increase plant selenium concentration, either by stimulating plant root growth and hence the plants absorbing capabilities, or by substituting for selenium in an insoluble soil complex, e.g., with iron oxides, releasing the selenium in an available form. Where superphosphates containing both sulfates and phosphates were added, variable results were obtained (Fleming, 1965).

Selenium deficiency may also appear as a result of changes in diet. It is most common in the winter when low quality feed is often used

(Shamberger, 1983). It may also be expressed when vitamin E content of the diet is lowered. Thompson and Scott (1969) showed that 0.01 µg/g selenium dry weight was adequate when the diet contained 100 µg/g vitamin E but that 0.1 µg/g selenium was required when the vitamin E level was dropped to 10 µg/g. Elements that complex or tie up selenium, e.g., cadmium, may also increase the requirement for selenium in the diet (Andrews, et al., 1981).

Selenium deficiency in poultry has been studied extensively (NRC, 1976). Feed supplements have largely eliminated the problem of selenium deficiency in commercial poultry production. The possible extent and seriousness of selenium deficiency in wild bird populations is unknown.

D. Selenium toxicity in mammals

The adverse effects of the excessive movement of selenium from seleniferous soil to plants and then to domestic animals and birds have been well documented in the north central United States (Moxon and Rhian, 1943; Anderson, et al., 1961). Rosenfeld and Beath (1964) describe three types of chronic selenosis in addition to acute poisoning. These are: a) the blind staggers, caused either by eating selenium accumulator plants, such as *Astragalus racemosus,* or by ingesting water-soluble selenium compounds from these plants; b) alkali disease, caused by eating plants or grains in which selenium is bound in the amino acids, and c) chronic selenosis produced by administration of excessive levels of selenate or selenite.

Acute selenosis leads to abnormal movement and posture, followed by labored breathing, diuresis, bloating and death (Martin, 1973). Blind staggers is characterized by nervous system disorder, wandering, stumbling, and eventually paralysis and death. Concurrent alkaloidosis may be responsible for some of these symptoms (Hartley, et al., 1985). Alkali disease includes retarded growth, emaciation, deformed hoofs, loss of hair and eventual death (Franke, et al., 1934).

Blood selenium levels of 2-4 µg/g are typical of selenosis but levels of 25 µg/g have been observed in acutely ill animals (Martin, 1973). The tolerance levels and toxic levels for selenium are shown below in Table 5.1. Chronic consumption of more than 4-5 µg/g appears to be inadvisable (Kubota and Allaway, 1972). These levels will vary depending on other components of the diet, general health, and the type of selenium compound.

Table 5.1. Selenium tolerance and toxicity levels, total rations

Species	Tolerance level	Toxic level
	µg/g of ration, dry wt	µg/g of ration, dry wt
Cattle	2.0	11.0
Sheep	--	10.0
Horses	--	3.3
Swine	2.5	15.0
Poultry	5.0	15.0
Rat	5.0	8.0

Miller and Williams, 1940a,b; Glover, et al., 1979.

The effects of ingesting plant material with high selenium content are insignificant if the amounts are small and the diet is otherwise complete (high protein, vitamin E, sulfur and methionine) and well-balanced (Glover, et al., 1979). Toxicity is commonly seen when the range is degraded and seleniferous plants, generally eaten as a last choice, are the primary available food.

E. Nutritional requirements for selenium

The dietary requirement for selenium is affected by the bioavailability of the selenium in the feed. Variables affecting bioavailability are not well understood, but differences are recognized factors and have been compared in a few studies (Hazell, 1985; Lonnerdal, 1985; Mason, 1985; Combs and Combs, 1986). It is known that food treatment can affect bioavailability. Laws, et al. (1986) found that selenium in freeze-dried meal was more bioavailable than meal dried at 82°C. Humaloja and Mykkanen (1986) explored the mechanism of selenium absorption in chickens and found selenomethionine crossed the epithelial tissue lining the intestine more rapidly than selenite salts.

Levels of 0.1-0.2 µg/g selenium in the diet of livestock are considered adequate (Kubota, et al, 1967; NAS, 1984a) and deficiency diseases typically become apparent when dietary levels fall below 0.05 µg/g selenium (Kubota and Allaway, 1972). The amount of selenium required may range from 0.03 to 0.10 µg/g depending on the level of vitamin E present (Underwood, 1966; Oldfield, 1971). Vitamin E and selenium are cofactors in the prevention of liver and muscle degeneration in rats; large amounts of vitamin E can offset some of the demand for dietary selenium and vice versa; although neither can fully substitute for the other. Both of these agents are therefore preventative in selenium deficiency (Oldfield, 1971). The higher vitamin E content of green forage can offset some of the dietary demand for selenium (Carter, et al., 1970).

The level of selenium in feed that is safe for animals is believed to be about 1 µg/g dry weight (Oakes, et al., 1977). The requirements for selenium vary widely with the form of the selenium ingested and with many other dietary factors (see also Chapter 3). Disorders in livestock may be expected when selenium concentrations in forage plants fall below 0.10 µg/g dry weight. Other threshold values, including a toxic level of 3 µg/g selenium and a minimum requirement of 0.1 µg/g, have also been proposed for grassland (Kitagishi and Yamane,1981). The acceptable levels for feed are included in Table 5.2.

Most feeds contain low concentrations of selenium and do not present a toxic hazard. In many cases, animals grazing on soils containing selenium-accumulating plants will consume these only if preferred feed is scarce, probably due to low palatability of these plants.

Table 5.2. Accepted selenium levels in livestock and poultry feeds, total ration

Species	Adequate level	Current maximum allowable
	µg/g dry weight	µg/g dry weight
Cattle	0.10-0.20	0.3
Sheep	0.10	0.3
Horse	0.10	
Swine	0.15	0.3
Poultry	0.15	0.3
Ducks	0.14	
Turkey	0.20	0.3

Sources: Combs and Combs, 1986; Food and Drug Administration, 1987.

F. Selenium toxicity and deficiency in livestock and wildlife in California

1. Toxicity

Accounts in the 1870's mention poisoning of livestock in California by locoweed, *Astragalus* spp. (Kellogg, 1875). More recent studies of *Astragalus* suggest that perhaps "most of the species in California are either not injurious or they are harmful only under certain circumstances" (Sampson and Malmsten, 1935). Cases of poisoning may have been caused by the alkaloids common in some of these plants, rather than by selenium (Hartley, et al., 1985; Molyneux, et al., 1985).

High selenium concentrations have been observed in very few plants in California. Some of the higher observed levels include 2,175 µg/g dry weight in *Astragalus crotalariae* growing in soil with 2.4 µg/g selenium at Truckhaven near the Salton Sea (Beath, et al., 1941); *Stanleya pinnata* (Princes' Plume) with 199 µg/g dry weight has been collected near Buttonwillow (Norman, 1987); and *Prosopis glandulosa* with more than 100 µg/g dry weight collected near Harpers Well (Bainbridge, 1988).

A single case of selenium poisoning of livestock has been discovered in California, after extensive interviews and reviews (Norman, 1987). In this case, cattle near Buttonwillow were apparently affected by eating Prince's Plume, *Stanleya pinnata*, in 1946.

While the effects of excessive selenium at Kesterson Reservoir have been well documented in fish and wetland birds (Chapter 4), Clark (1987) was unable to demonstrate any adverse effects of selenium on mammals. He concluded that mammals seem much more resistant to the effects of selenium induced embryonic abnormality than birds. Food chain increases in selenium concentration were observed and higher level predators such as the San Joaquin Kit Fox, *Volpes macrotis mutica*, might experience reproductive difficulty.

2. Deficiency in livestock

In California, selenium-deficient soils and plants are routinely found on the eastern side of the San Joaquin Valley; in most areas of the northern part of the State; and many parts of the Coast Range (Carter, et al., 1960; Williams, et al., 1982; Kubota and Allaway, 1972; and Norman, 1987). Ninety six percent of the forage sampled in Northern California had selenium concentrations below 0.10 µg/g (Carter, et al., 1960).

There is some uncertainty over what constitutes an adequate selenium blood level in sheep and cattle and values from 0.01 µg/ml to 0.20 µg/ml have been proposed as minimally adequate (Williams, et al., 1982). However, in California, blood selenium levels above 0.08 µg/ml are considered adequate and levels of 0.04 µg/ml or below are regarded as deficient (Nelson and Miller, 1987; Norman, 1987). There appear to be some differences between breeds in selenium requirements or metabolism (Williams, et al., 1982).

Selenium deficiency in livestock is widespread in California and supplementation to improve selenium status is common in many areas of the state (Williams, 1980; Williams, et al., 1982; U.C. Vet. Med., 1984; Norman, 1987). Counties with mean blood selenium levels in cattle less than 0.05 µg/g include Butte, Del Norte, Humboldt, Inyo, Lassen, Madera, Mariposa, Mendocino, Modoc, Napa, Nevada, Placer, San Joaquin, Shasta, Siskiyou, Sonoma, Stanislaus, Sutter, Tehama, Tulare, and Yuba county (Williams, 1980; Dunbar, et al., 1984). Herds with white muscle disease in Northern California had a group mean herd selenium blood level of less than 0.031 µg/ml (Williams, et al., 1982). Recent studies in the vicinity of Kesterson Reservoir (Bureau of Animal Health, 1986) demonstrated selenium deficiency in much of the lifestock in that area as well.

3. Selenium deficiency in wildlife

The California Department of Fish and Game has been analyzing blood selenium in game animals for several years (Jessup, 1987; Smith, 1987). These studies suggest that selenium is often borderline or deficient in these mammals by cattle standards. Preliminary analysis of experimental results suggests that selenium supplementation may have almost doubled fawn survival in northeastern California (Fleuck, 1988; Jessup, 1987; Norman, 1987; Smith, 1987). The results from this deer study, existing data on blood selenium levels of game animals, and preliminary maps of possible selenium deficient areas suggest that selenium deficiency may be a factor in poor reproduction of game animals in California (Jessup, 1987). The top counties for deer hunting in 1987 included Mendocino, Trinity, Siskiyou, Lassen, Shasta, Tehama, Modoc, Plumas, Humboldt, and Mono counties (Callas, 1988). Low selenium levels have been detected in livestock in eight of these counties and would be expected in the ninth, Mono, although no sampling has been done.

The long-term data on deer herd reproduction in Shasta County suggests that selenium deficiency may be a relatively recent development (Smith, 1987). Possible reasons for the suspected decline in plant selenium levels in the diet of these animals and consequently low selenium blood levels are unknown. They may be related to changes in range management. Burning to remove perennial brush and shrubs may volatilize, and thereby remove much of the selenium. The general deterioration in range quality as a result of many years of grazing may also be implicated. The removal of more nutritious forbs, shrubs, and trees by over-grazing or management techniques may reduce selenium availability and uptake. For example, the shift from forbs to grasses under grazing pressure could reduce the selenium content of the diet from 5-10 fold. The reduction or elimination of shrubs could result in equally large reductions in selenium content of browse. This would be sufficient to change marginally sufficient diets to clearly deficient diets. Sulfur deposition from the atmosphere may make selenium less available and reduce dietary selenium levels. The mountain lion and coyote may have been unfairly blamed for declines in deer population that were caused by poor nutrition.

Birds, both domesticated and wild, also develop selenium deficiency diseases. Reduced growth, muscle myopathy, pancreatic degeneration, exudative diathesis, lesions, and myocardial failure have all been related to selenium deficiency in birds (Creech, et al., 1957; Patterson, et al., 1957; Schwarz and Foltz, 1957; Rahman, et al., 1960; Scott, et al., 1967; Thompson and Scott, 1970; Pond, et al., 1971; Gries and Scott., 1972; Scott, 1973; Combs and Combs, 1986). Dietary selenium of about 0.05-0.06 µg/g dry weight of feed is needed to prevent exudative diathesis in chicks (Mathias and Hogue, 1971; Scott and Thompson, 1971; Noguchi, et al., 1973). Conservative recommendations for the dietary selenium requirements of chickens, ducks, and turkeys are between 0.1 and 0.2 µg/g dry weight (NAS, 1984b).

Selenium deficiency in resident California birds might be expected to occur in areas where cattle and deer exhibit deficiency diseases but this co-occurrence has not been reported in the literature. This may simply reflect the limited research that has been done, or differences in food sources.

Selenium supplementation may prove of value in improving the survival of mammals and birds that are suffering from selenium deficiency. Selenium supplements may also provide protection against pesticide contamination. As Combs and Peterson (1983) found, increased selenium, (0.10 µg/g sodium selenite in the diet) tripled the LD_{50} for parquat in chicks. Increased selenium intake may be desirable in areas with polluted water or contaminated food.

4. Remedies for selenium deficiency

Selenium deficiency diseases can be treated or prevented by injecting selenium as selenite with vitamin E, the most common treatment in livestock in California (Norman, 1987). Selenium-rich drenches have also been used, as has provision of selenium salts in water. Salt blocks, with at least 100 µg/g selenium, have been effective in California. The standard salt-block mix, with only 20 µg/g, was not effective in a 160 herd comparison study in California (Norman, 1987). Other studies have found that 300 µg/g in salt blocks was required to elevate blood selenium levels to desired levels (Hathaway, et al., 1980). The administration of selenium-enriched pellets inserted in the rumen is also being used on a large trial basis in California with very encouraging results in both cattle and deer (Norman, 1987; Nelson and Miller, 1987; Jessup, 1987; Fleuck, 1988).

The benefits of selenium supplementation of cattle were demonstrated in a recent study in the Sierra foothills near the Fresno-Tulare County line (Nelson and Miller, 1987). Two thirty-gram pellets (ten percent elemental selenium and ninety percent iron) were administered to selected selenium-deficient cows. This treatment increased the birth weight of calves produced by these cows by more than eight percent. This was accompanied by earlier delivery which may also be advantageous. These rather dramatic results led to a study of the effects of a combined treatment of selenium and vitamin E for calves born to the same herd in 1986. Male calves born to untreated cows with low blood selenium were injected with a solution of selenium and vitamin E. At the conclusion of the experiment, treated calves were 111 pounds heavier than the controls. Male calves born to cows previously treated with selenium and then (themselves) treated with an injection of a selenium and vitamin E solution gained 47 pounds more than controls (Nelson and Miller, 1987). The response of female calves of untreated cows to injections was significant but smaller.

The addition of selenium to the soil as a topdressing has also been shown to be an effective and safe method for preventing selenium deficiency in livestock (Grant, 1965; Watkinson, 1983). While individual treatment has proved inexpensive and convenient for young livestock, topdressing fields with selenium provides longer term protection and is better suited for operations with large numbers of mature animals. Topdressing is effective under high or low rainfall conditions and on all classes of selenium-deficient soil (Watkinson, 1983).

Application rates for selenium soil-amendments will depend on the soil type, type of vegetation or crops, and other factors (Grant, 1965; Allaway, et al., 1966; Gupta, et al., 1982; see also Volume 1, Chapter 5). Application rates of 10 g selenium/hectare are permitted in New Zealand, which should provide a safety factor of 10-20 times (Watkinson, 1983). This is often mixed with regular fertilizer and used as a topdressing, which may be applied by aircraft (Watkinson, 1983; Selcote, nd). Some fertilizers, such as the superphosphate made from seleniferous rock phosphate, may also provide protection against selenium deficiency when applied to soil (Robbins and Carter, 1970).

Foliar application is potentially efficient and safe for increasing selenium in forages and feeds (Watkinson and Davies, 1967; Gissel-Nielsen, 1975; Gupta et al., 1983). Foliar application of selenium supplements was found to be more efficient for some plant species than others.

G. Summary

Selenium toxicity in the terrestrial environment appears to be very uncommon in California and poses no known problems for livestock and few, if any, problems, for wildlife. Selenium-deficiency diseases and selenium levels below what is considered adequate are common in livestock in many areas of California and selenium supplementation of livestock with injections, salt block, selenium-enriched feed, and selenium-iron pellets for the rumen has demonstrated significant benefits. Selenium deficiency has also been observed in wildlife and selenium supplementation has greatly improved the survival of deer fawns in a selenium deficient area. Feed for poultry and other domestic animals is routinely supplemented with selenium to prevent selenium deficiency diseases. Selenium-deficient areas can also be treated with selenium amendments for the soil to increase the selenium content of feeds and forage to desired levels.

Selenium deficiency in the wildlife and birds of California have been inadequately studied, and until further studies are completed, few answers can be given to the many questions about the distribution and importance of selenium deficiency in California. However, livestock in eight of the nine top counties for deer hunting have been found to be selenium-deficient, which strongly indicates that selenium supplementation studies should be undertaken in these areas.

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Chapter VI. Disposal and Treatment of Agriculturally-generated Selenium-containing Wastewater

The means for treatment and removal of undesirable salts and trace elements from subsurface drainage water are not currently available at a price that agriculture will pay.

Lee, Nishimura, and Hansen 1988

A. Introduction

There are several interrelated strategies for dealing with selenium problems generated by irrigated agriculture and drainage. No one strategy alone is likely to meet all the environmental, wildlife, and human health concerns currently facing natural resource managers. Combinations of strategies are most likely to emerge as proposed solutions. Emphasis has been placed on the problem of excess selenium rather than on selenium deficiency, for although selenium deficiency appears to be more widespread, its solutions are relatively straightforward and non-controversial. Solutions for dealing with excess selenium contamination are neither. These solutions may involve combinations of biological and engineering-technological options. The nature and extent of the contamination will largely determine the solution.

The effectiveness of these processes depends on many factors which are not well understood. For example, the characteristics of drainage water vary with the time of year and drainage source. In addition, the interactions between and among a wide range of chemical factors and concentrations of dissolved ions, including heavy metals and salts, can alter the effectiveness of each process. Nitrates, sulfates, total organic carbon, and pH are particularly important. And finally, the microbial and plant responses in some of these systems are not well understood and may change over time, compromising effectiveness. Basic research on many of these proposed processes is still needed to develop systems that will work over the long term and be cost-effective.

B. Biological treatments

Several technological developments have emerged from both the private and public sectors for treating contaminated water, soils, and sediments using biological methods. Most of these involve the use of specific microbiological techniques recently developed specifically for selenium contamination.

1. Bacterial treatment

Binnie California, Inc., a subsidiary of Binnie and Partners from London, a private engineering consulting firm, has conducted demonstration projects to treat selenium-contaminated drainage water. Proprietary concerns have limited disclosure of the precise methodology but more information should be forthcoming. A generalized description of the process is presented here. Basically, it involves anoxic packed bed microbial reactors into which contaminated drainage water is introduced. A carbon source (such as locally available molasses) is introduced to stimulate biological activity. Bacteria in the reactors then take up the selenium. The reactors retain this mixture for a specified time, after which it is passed into a holding tank, and then the bacteria are filtered out (Letey, et al., 1986; Fraley, et al., 1987).

Initial results were promising and a preliminary report showed the Binnie California process could reduce the selenium concentration to below 10-40 µg/L after microfiltration (Lee, et al., 1988). Consistently meeting a 10 µg/L standard would require polishing with ion exchange resins. The plant has now been idled and there are apparently no plans to continue work (Benson, 1988). The cost for treating drainage water was estimated to range from $145-224 per acre foot, not including disposal costs for collected trace elements and salts (Lee, et al., 1988).

Currently, the Drainage Program is funding laboratory research by the University of California, Davis, on the theoretical basis of the process (SJVDP, 1987a).

2. Algal treatment
Selenium uptake by *Cyanobacter* (blue-green algae) has been investigated in the laboratory (Oswald, 1985). It has been reported that these microorganisms can concentrate selenium from water tenfold (Packer, et al., 1986). The process requires light and oxygen for photosynthesis, but the rapid and expansive growth without the need for an added carbon source suggests it has some potential. This process has been able to reduce selenium concentrations in water from 359 µg/L to 20 µg/L in the laboratory (Lee, et al., 1988). The bioconcentrated selenium could be harvested mechanically through centrifugation and filtration. Food supplements have been suggested as a potential end use and income generator. Much more research is needed, especially beyond the laboratory scale, to evaluate the usefulness of this process.

   The Drainage Program is currently funding continued work to develop high-rate microalgal ponds. The next step in the research is laboratory and field-level studies necessary for a detailed engineering evaluation of the process and preliminary design of a pilot plant (SJVDP, 1987a).

3. Volatilization by fungi
The first step in the treatment program may be volatilization by soil fungi (Frankenberger, et al., 1987). Fungal activity is stimulated by adding carbon sources, maintaining soil moisture and aeration, and adding nutrients. Initial lab and field studies have been promising, with initial field volatilization rates reaching a maximum of 363 $\mu g/m^2$/hour (Frankenberger, 1988). This treatment may be able to

remove much of the selenium from the surface layer. This process should also improve soil characteristics for subsequent plantings by increasing the soil organic matter and providing some leaching of salts.

4. Bacterial reduction
   The ability of facultative bacteria to reduce selenium has been demonstrated by the Bureau of Mines. Initial laboratory studies have been encouraging. This process could perhaps be run in open reactors and might not be as expensive as systems requiring closed reactors (Lee, et al., 1988).

5. Harvesting or volatilization with vegetation
   Treatments based on vegetation management have not been explored in depth but preliminary studies suggest they offer the potential of both low cost and potential economic return from the treatment program (Bainbridge, 1988). These treatments are generally simple, relatively inexpensive, and adapted to on-farm operation. However, the full potential of these methods will not be known until further studies are completed. These treatments include both harvesting and removal and volatilization.

   Selenium in the soil can be concentrated and collected in plants. This was first suggested by Beath (1959), who calculated the potential selenium harvest from *Astragalus bisulcatus* could reach almost 7 kg/(ha yr) with a good recovery process. The seleniferous plant material can then be used as fuel for a power plant (with appropriate selenium scrubbers), processed as a selenium-enriched feed for animals in selenium-deficient areas, or used as a selenium-rich soil amendment for selenium deficient soils (Bainbridge, 1988; Cervinka, et al., 1987, Cervinka, 1988). The viability of biofuel power production has been confirmed by studies conducted by the California Energy Commission (Eden, et al., 1988). The flyash from the biofuel power plant might be used as a soil selenium amendment. Use as either feed or soil supplement appear feasible because selenium-deficient soils and animals are common east of the San Joaquin River.

   The end use will determine whether the goal of harvesting selenium with vegetation should be maximum uptake or maximum palatability with modest uptake. The technology and equipment for wetland harvesting lags behind that available for dry lands, but the productivity of wetlands can be higher and may be worth further development.

   The pilot and laboratory studies that have been completed suggest that this type of treatment has considerable potential (Bainbridge, 1988). The plants for selenium harvesting may either be known selenium accumulators, e.g. *Astragalus,* that may contain selenium concentrations thousands of times those in soil, or plants that only reach concentrations several hundred times as high as soil levels (Bainbridge, 1988).

C. Chemical treatments for selenium contamination

1. Ion exchange

The use of selective ion exchange resins to remove selenium ions from water has been evaluated by several investigators (Herrmann, 1985; Maneval, et al., 1985; Boegel and Clifford, 1985; and Klein, 1986). A private firm, Boyle Engineering is currently conducting exploratory studies with currently available resins and with manufacturers who are developing new resins for selenium removal.

An ion exchanger contains a solid matrix with fixed charged functional groups which behave much like a filter. The counterions attached to these functional groups allow target species of ions, e.g. selenate, to be trapped or collected on the ion exchanger surfaces (Paterson, 1970; Vermeulen, et al, 1984; Janauer, 1986; Ma, et al, 1982; Rodriquez, 1986; Naden and Streat, 1984).

Much more research is needed to investigate the effectiveness of this treatment, especially in light of the varying and complex chemical nature of drainage water. These factors, particularly the high sulfate and salt concentrations, could complicate ion exchanger design, performance, and operating cost.

2. Reverse osmosis

Reverse osmosis (RO) uses a thin membrane which separates water from a specific ion or ions using principles of diffusion and applying pressure (200-1500 pounds per square inch) to overcome osmotic pressures developed by solute concentrations (Considine and Considine, 1983). The rejection of selenium by reverse osmosis depends on selenium speciation, pH, composition of the predominant salts, product water flux, product water recovery, and other factors (Sorg and Logsdon, 1976; Hoornart, 1984; Eisenberg and Middlebrook, 1986; Marinas and Selleck, 1986; Hild, 1983; Burns and Roe, 1979).

The removal of selenate should be more or less independent of pH. Selenite removal should increase with pH. Removal of selenate and selenite was about 97 percent in municipal water spiked with a known quantity of selenium (Sorg and Logsdon, 1976). Low molecular weight, uncharged organic species of selenium will probably pass through a RO membrane and could not be removed with this technique (Marinas and Selleck, 1986).

Selenium acts as a weak electrolyte in aqueous solution. Weak electrolytes do not carry a sufficient charge at low pH to be rejected by the RO membrane and may pass through. This may influence the choice of pretreatment options for RO plants. pH could be manipulated chemically or biologically to improve RO performance. Pretreatment was found essential for successful RO operation with agricultural drain water (CH2M Hill, 1986). Chemical and biological pretreatment may be used to lower sulfate levels and improve RO operation. Pretreatment required for a 10 million gallons per day RO plant would include multimedia filtration, chlorination, and dechlorination. Lime soda ash appeared to have the lowest cost per gallon of pretreatment. RO recovery of 83-87 percent appeared feasible. Estimated cost ranged from $1,150-1,280 per acre foot (SJVDP, 1987a) per year. Major disadvantages include high cost, energy requirements, and the need for extensive pretreatment (Longley and Hanna, 1986). Water softening, required for RO, results in a predominantly sodium product water, which is undesirable for irrigation. The low-electrolyte, high-sodium water causes soil dispersion, which seals the soil and greatly impedes water infiltration (Letey, et al., 1986). Boron removal by RO is variable, depending on the selectivity of the membrane, so the product water may contain boron.

A RO plant may also be operated to desalinize water. This has been explored for a number of purposes, including agricultural wastewater and seawater (Yamamoto, 1983; Scott, 1981; Antonuik and McCutchen, 1973; Johnson and Loeb, 1966). Pretreatment may be essential for these applications as well (Strenstrom, 1983).

3. Activated alumina

Activated alumina will selectively remove some species of arsenic, fluoride, phosphate, silica and other anions from water with little interference from other cations and anions commonly present at higher concentrations (Kreft and Trussell, 1986). Activated alumina has recently been tested as a treatment for selenium removal from water (Trussell, et al., 1980; Ghosh and Yuam-Pan, 1985).

Sulfate and bicarbonate interfere with selenate adsorption and reducing alkalinity in the solution will increase capacity for selenate removal. Selenate, being lower in the selectivity series than selenite, is more susceptible to interference and competition from other ions (Kreft and Trussell, 1986). Selenate removal by alumina is not as efficient as selenite removal.

No methods have been developed to reduce selenate to selenite economically although microbiological methods are promising. Agricultural drainage water with very high sulfate levels, e.g., up to 4,500 mg/L at Kesterson Reservoir, would probably not be treatable with the activated alumina process when the majority of the selenium is selenate (Longley and Hanna, 1986). If a significant proportion of the selenium is selenite, this process might provide cost-effective treatment. Chemical or biological treatment might be used to change selenate to selenite or to lower the sulfate level, thereby improving the operation of the activated alumina treatment process.

4. Coagulation - alum or lime softening processes

   Selenium salts can be removed from water by coagulation. Selenate salts are generally more soluble than the corresponding selenite salts. As a result, more selenite than selenate should be removed by both conventional coagulation and lime softening. Because selenate and sulfate chemistries are similar, both processes may be ineffective for selenate removal, due to high sulfate concentrations in the contaminated waters, unless both species can be removed at once.

   Little information exists on selenium removal by conventional water treatment and lime softening processes. Although these results do not apply directly to selenium contaminated water treatment, the work is related and provides some insight into the potential value of these water treatment processes (Sorg, 1986). These studies show that selenite is more readily adsorbed than selenate, and that selenite adsorption is pH-dependent. The laboratory and pilot plant studies that have been conducted suggest that conventional coagulation and lime softening treatment process methods are ineffective for selenate removal, and only moderately effective for selenite removal (Sorg, 1986).

   The general conclusions drawn from the drinking water and wastewater studies include the following: conventional water treatment techniques are ineffective for selenate removal; no more than 10 percent removal is achieved using alum or lime softening; lime softening can achieve 20-40 percent removal of selenite; increasing pH increases removal (pH 11 was better than pH 9); alum is least effective for selenite removal, with only 10-20 percent removal efficiency; selenite can be oxidized to selenate by chlorine, so pre-chlorinization will decrease the removal of selenium (Longley and Hanna, 1986; Sorg, 1986).

5. Iron filings

   Harza Engineering Co. has completed initial studies of selenium removal through their patented iron filing process. It included four months of small pilot operation at the Panoche Water District, bench scale tests, and analyses of data to develop design conditions and to develop planning level costs. A larger pilot plant is under construction (Harza, 1986; Letey, et al., 1986).

   Agricultural drainage water is pumped through a layer of iron filings to which the selenium is adsorbed on surfaces. Water containing 160 mgSe/L, treated for up to 6 hours, contained as little as 10% of the original concentration. Treatment facilities can be designed for various levels of selenium contamination, desired reduction efficiencies, life span, and volume of drainage water to be treated.

A pilot prototype plant will be tested at the Panoche Drainage District (Lee, et al., 1988). This research may resolve some of the questions which remain prior to large-scale application of the process. These include: verifying the adsorption process which makes selenium removal possible; identifying and overcoming conditions which cause the iron filings to clog in the columns (SJVDP, 1987a). Work currently involves expansion of the tests at the laboratory and field level to demonstrate the technical and economic feasibility of the process for removal of selenium and other trace elements from agricultural drainage water. Costs for 75% removal were estimated to be about $285 per acre foot (Lee, et al., 1988).

6. Iron coagulation
   Iron coagulation is the most effective conventional water treatment method for the removal of selenite from water, with removals of 60-80 percent. Selenium removal increases as the pH of the treated water decreases, with best results at pH 7 or lower (Olson and Jensen, 1940; Plotnikov, 1958, 1960, and 1964). This poses problems for high pH drainage waters. Selenate removal through iron coagulation is much less effective, on the order of 10 percent (Sorg, 1986).

7. Iron hydroxide
   Laboratory bench studies have been conducted by the U. S. Bureau of Reclamation Engineering and Research Center in Denver on the reduction and removal of selenates from water using iron hydroxides (Moody, et al., 1988). Field studies at Murrieta Farms selenate was reduced 90% in 2 hours (Lee, et al., 1988). More work is needed to test effectiveness in the field.

8. Vapor-compression-evaporation
   In 1985, DWR contracted with Bechtel Corporation for a demonstration of the vapor compression evaporation (VCE) technique for desalinization (Letey, et al., 1986). Basically, the water to be treated is evaporated, concentrating the salts in the remaining solution, and the "pure" evaporated water is condensed.

   VCE is costly with estimated direct treatment cost of approximately $2,000 per acre-foot. This estimate includes the cost of reject water disposal in lined ponds.

   Many other ideas and theories have been suggested for selenium removal from water, soils, and sediments. A few show some potential but only in combination with the above-mentioned processes. Many studies involve desalting technologies which are modifications of reverse osmosis and ion exchange. Other applications of technology are attempting to combine treatments with potential economic benefits such as power generation in solar salt-gradient ponds.

D. Disposal

Disposal is often appealing due to low cost, but has a history of secondary or tertiary impacts that were not originally anticipated. The problems that developed at Kesterson Reservoir are a good example.

1. Drainage to the Delta or the Pacific Ocean

   The original plan for removal of drainage waters from the San Joaquin Valley had been to transport them to the Delta (Letey, et al., 1986). This plan was first abandoned because of rising costs, but the subsequent discovery of the selenium problems at Kesterson Reservoir makes it unlikely this would ever be allowed (Tanji, et al., 1986). The possibility of transporting these drainage waters to the Pacific has also been discussed but the high cost and political volitility of this option have made it difficult to pursue.

2. Deep well injection

   The use of deep well injection is currently being evaluated (Letey, et al., 1986), but this is also costly and may not be free of risk. Similar disposal of wastes in the Denver area led to a series of earthquakes (Healy, et al., 1968). Possible effects of deep-well injection on the transverse faults of the San Joaquin Valley should be evaluated. Site conditions and operating conditions must be carefully reviewed to prevent ground water contamination.

   Westlands Water District has developed plans for a prototype injection well near Mendota. The Drainage Program will closely observe the Westlands tests and use the information developed in further evaluation of this option.

3. Evaporation ponds

   Evaporation ponds have been the most common solution for disposing of agricultural drainage water. The substantial land requirement (approximately 10-20 acres of pond for each 100 acres of drained land) and the ultimate problem of disposal of accumulated salts and minerals present are serious concerns (Letey, et al., 1986). Other shortcomings include possible ground water contamination by waters percolating below the evaporation pond, and danger to wildlife exposed to toxic conditions in the pond (Lee, et al., 1988).

   Strategies to protect ground water from contamination with selenium tend to run counter to strategies to protect wildlife, leading to difficult choices and trade-offs. Protecting ground water from selenium contamination from evaporation ponds can be aided by encouraging algal and plant growth in the pond. The algae and plants remove selenium from solution and convert it into a relatively immobile, organic form. Anaerobic zones will develop in the bottom of the pond when plants die, sink, and decompose. Selenium can be methylated and volatilized to the atmosphere or reduced to selenite or elemental selenium in these anaerobic zones (Weres, et al., 1985; Weres, 1987; Benson, et al, 1988). However, protectors of wildlife do not want the ponds to contain plants and algae with selenium in organic forms that could then be concentrated in the food chain.

Evaporation ponds can be constructed either on individual farms or on a regional basis. Regional ponds can more easily be constructed on nonproductive land, while productive land may have to be sacrificed for on-farm ponds. Rather large increases in overall costs to a farmer occur when an evaporation pond must be constructed on productive land (Dinar, et al., 1985). Poor pond management possibilities increase as the numbers of on-farm ponds and operators increase. The workload for the Regional Board is much greater with on-farm ponds than with regional ponds because its effort is primarily related to the number, rather than the size, of the ponds (Letey, et al., 1986).

On the other hand on-farm ponds keep the pollutants in the area where they have been generated and allow segregation of waters of different qualities, whereas regional ponds blend the waters with an end product of intermediate concentration. One argument for keeping waters segregated is that waters low in toxics may need less treatment than the entire volume of blended water.

A related argument for on-farm ponds is that the potential for ground water contamination by percolation from the pond is reduced because the percolate is returned to the zone of its origin. High selenium pond waters percolate to high selenium water and low selenium pond waters percolate to low selenium water. Treating drainage water to remove selenium or other toxics may ultimately be necessary to protect the environment.

The economic feasibility of evaporation pond construction is directly linked to irrigation management, which controls the amount of water requiring disposal. On-farm ponds provide a direct feedback to the farmer and, therefore, incentive for improving irrigation management. The same effect could be achieved with regional ponds, if the drainage from each farm was monitored and the farmer was assessed a fee proportional to the discharge volume.

Significant trade-offs exist between regional and on-farm ponds. No clearcut advantage for either is recognized. Unless, or until, an overall management plan is adopted for the valley, decisions will be made by default rather than logic (Letey, et al., 1986).

There are now 27 pond systems totalling more than 7,000 acres and many more are being planned (CVRWQCB, 1988). The Central Valley Regional Board has received applications for ponds covering about 10,500 additional acres, and the Regional Board has projected that acreage requested for ponds could double in the next 5 to 10 years (SJVDP, 1987a).

4. Disposal to the San Joaquin River
In 1985, 84,000 acres of the San Joaquin Valley were being drained and an additional 167,000 acres required drainage (Tanji, et al., 1986). Currently, about 48,000 acres of farmland in the Drainage Study Area (discharging primarily to Mud or Salt Slough) of the west side of the valley have subsurface tile drains that eventually discharge into the San Joaquin River (SWRCBTC, 1987). This subsurface drainage is a serious concern for wildlife and fish in the San Joaquin River system. The standards adopted for disposal to the river will help determine what level and what type of treatment will be suitable. The ultimate costs of treatment and the allocation of this cost will determine how farming operations change.

The estimated cost of proposed solutions are shown as Table 6.1.

The development history of treatment plants of this type has not been encouraging. The Colorado River desalinization plant at Yuma, Arizona is a good example. This was first proposed in 1970 at an estimated construction cost of $178 million and $12 million per year in operating costs (Sheridan, 1981). By 1987, the official cost of the plant had risen to $293 million dollars, with related non-plant costs estimated at $600 million (Reisner, 1987). Operation and maintenance could push the total cost to more than a billion dollars over the next 50 years (Reisner, 1987). The treatment cost is more than 300 dollars per acre foot at the plant (Reisner, 1987). It may have been cheaper to buy the land and remove it from production than it is to treat the salty drainage water (Sheridan, 1981; Reisner, 1987).

E. Conclusions

There are a number of options for treating agricultural drain water to remove selenium. The chemical-engineering methods are not feasible "at a price agriculture will pay" (Lee, et al., 1988). The biological methods are likely to be more economical but remain unproven. Volatilization with fungi and harvesting with algae are closer to application than harvesting and economic return to offset the cost of the treatment process. The reduction of drainage volume and improvements in farm water use are most important over the near future (Chapter 2).

Table 6.1. Alternative treatment processes.

Process	Development stage	Estimated cost
		$ per acre-ft[a]
Bacterial (Binnie)	Pilot prototype	150-225[c]
Iron filings removal[c]	Pilot prototype	120-285 for 75%
Iron hydroxide	Pilot mini-batch	100-150[c]
Algal/bacterial	Pilot mini-batch	75-150[c]
Ion exchange	Laboratory bench	300[b,c]
Reverse osmosis	Pilot prototype	980-1,220[c]
with waste pond		1,650-2250
Vapor compression evaporation		2,000
Deep well injection		189

[a] For 10 million gallon per day plant.

[b] based on Yuma estimates, smaller sized plants for selenium would possibly be much higher

[c] plus disposal, $50 to $500 plus per acre foot.

Sources: CH2M Hill, 1986; Letey, et al., 1986; Sheridan, 1981; SJVDP, 1987a, b; Lee, et al., 1988.

Any attempt to reduce selenium contamination of drain water must consider the economic incentives that currently drive the system.Treatments should be selected on a basis that provides net benefits to society--rather than net costs. It may be most appropriate to consider options that revise existing economic incentives to more accurately reflect external costs. Among these options are the following:

- The development of more open water transfers and marketing;
- Regulations, such as Title 23 Subchapter 15 of the California Administrative Code, regulating disposal of liquid waste. The desire to avoid risk, including the risk of future liability and litigation, may be important .
- Alternatives such as agroforestry, dryland grain, recreational hunting and fishing, or grassland grazing could provide better returns to land owners than traditional cropping patterns when external costs are factored in.

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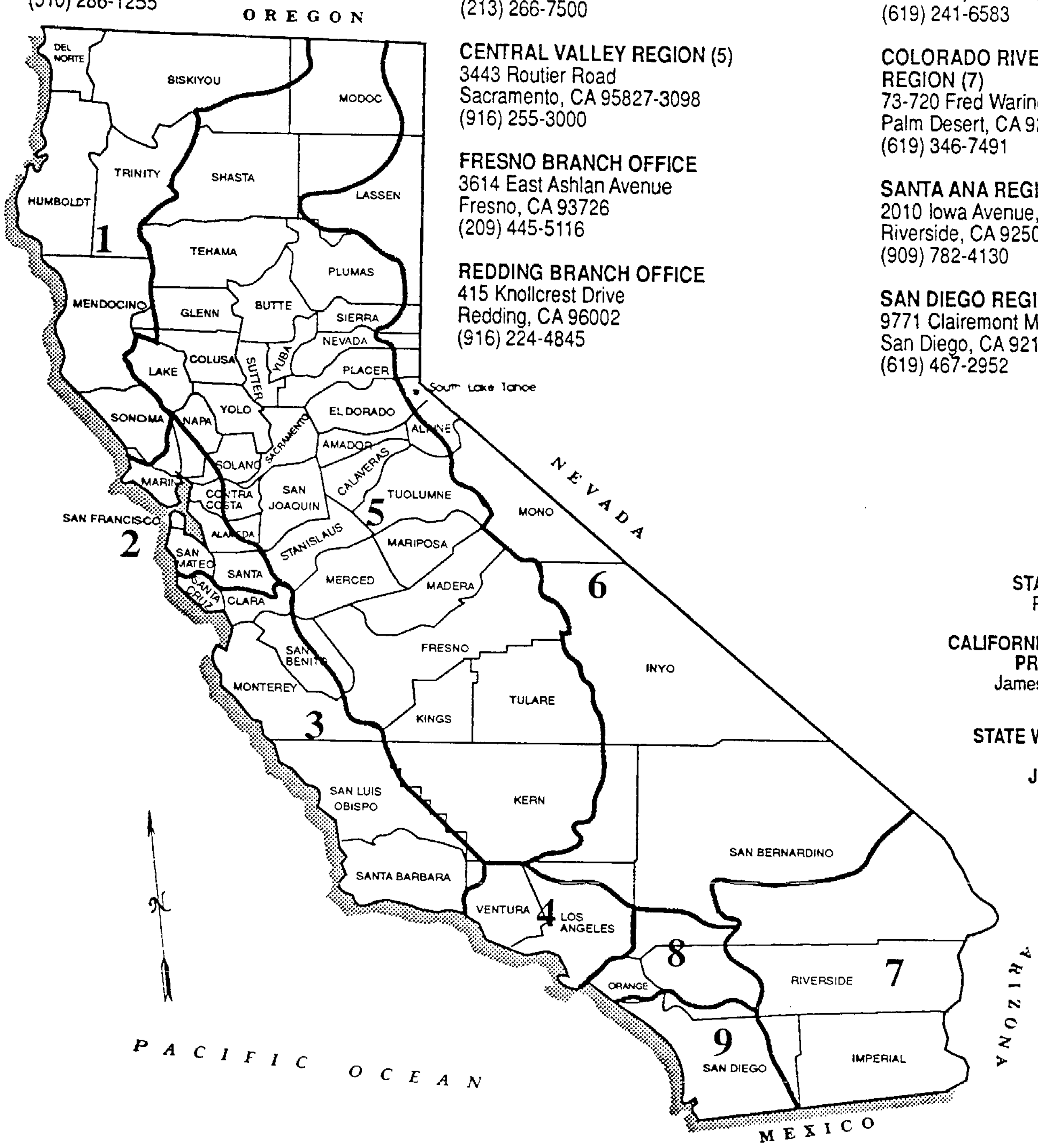

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