Chapter 1

SUBSURFACE AGRICULTURAL DRAINAGE IN CALIFORNIA'S SAN JOAQUIN VALLEY

Randall L. Brown and Louis A. Beck

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I. INTRODUCTION

The objective of our chapter is to set the stage for subsequent presentations and discussions in this book by describing the history of the San Joaquin Valley drainage problem and the environmental issues surrounding it. The description focuses on drainage from California's San Joaquin Valley; however, the material on environmental concerns and salt balance is relevant to other areas of the world where similar problems exist.

The San Joaquin Valley (Figure 1) has long been one of the world's richest agricultural areas. In 1979, the value of crops produced in the valley was estimated at $7 billion.' California's Mediterranean climate results in winter rains and hot, dry summers. This climate pattern and the long growing season cause valley farmers to rely on irrigation. Irrigation water is derived from groundwater pumping, transfer from storage reservoirs in the Sierra Nevada mountains to the east, and state and federal water projects that bring in water from the Sacramento-San Joaquin Delta to the north.

At present, about 2 million ha of the San Joaquin Valley are irrigated with about 7 km^3 of water annually. In much of the valley, irrigation causes few direct environmental problems, although there are concerns associated with the various diversions used to provide the needed water. On about 200,000 ha, however, irrigation has resulted in problems caused by poor drainage. These lands, located mainly on the valley's west side, are underlain with almost impermeable clay layers that severely limit the downward penetration of water. Depending on the hydraulic gradient, portions of the applied water can accumulate in the root zone beneath the irrigated fields or can flow downslope and cause similar problems on the valley floor. Evapotranspiration from plant surfaces and dissolution of native soil minerals cause the salt content of the percolating water to increase to levels where it is not easily recycled as irrigation water.

The most common solution to the drainage problem on the west side has been to install artificial drains at field depths of 2 to 3 m. Figure 2 illustrates how these permeable drains collect the perched water and lower the water table to below the root zone. About 50,000 ha of land with high water tables in the San Joaquin Valley have been drained in this fashion.

This physical solution has transferred the salty water from beneath the farmers' fields to other areas. In California's Imperial Valley, which borders on Mexico to the south, about 200,000 ha of farmland have been drained in a similar manner. The drainage goes to a confined natural salt sink, the Salton Sea, which for years has sustained California's most productive inland fishery. Because of the sea's high salt content, the fishery consists of marine species imported from the Gulf of California plus such salt-tolerant species as tilapia.

As long as the amount of land drained in the San Joaquin Valley remained relatively modest, much of the drainage in the northern valley flowed to the San Joaquin River and out to sea by way of the Sacramento-San Joaquin Delta. (Water from the southern valley could not take this pathway because of a natural slight rise in the valley floor which usually hydraulically isolates the Tulare Lake basin from the San Joaquin River.) However, as drainage volumes built up, there were valid concerns that beneficial uses of the San Joaquin River would be degraded by discharge of too much salt and possibly other harmful materials to the river. These concerns led to several attempts to find other means of resolving drainage-related issues. The remainder of this chapter describes the issues themselves and summarizes the various formulations developed to respond to the issues.

II. DRAINAGE WATER QUALITY AND QUANTITY

Irrigation water applied to the fields is generally of high quality, with concentrations of total dissolved solids less than 500 mg/l. Evapotranspirative processes result in pure water leaving the plant surfaces, with the residual salts being left in the soil profile. Farmers apply

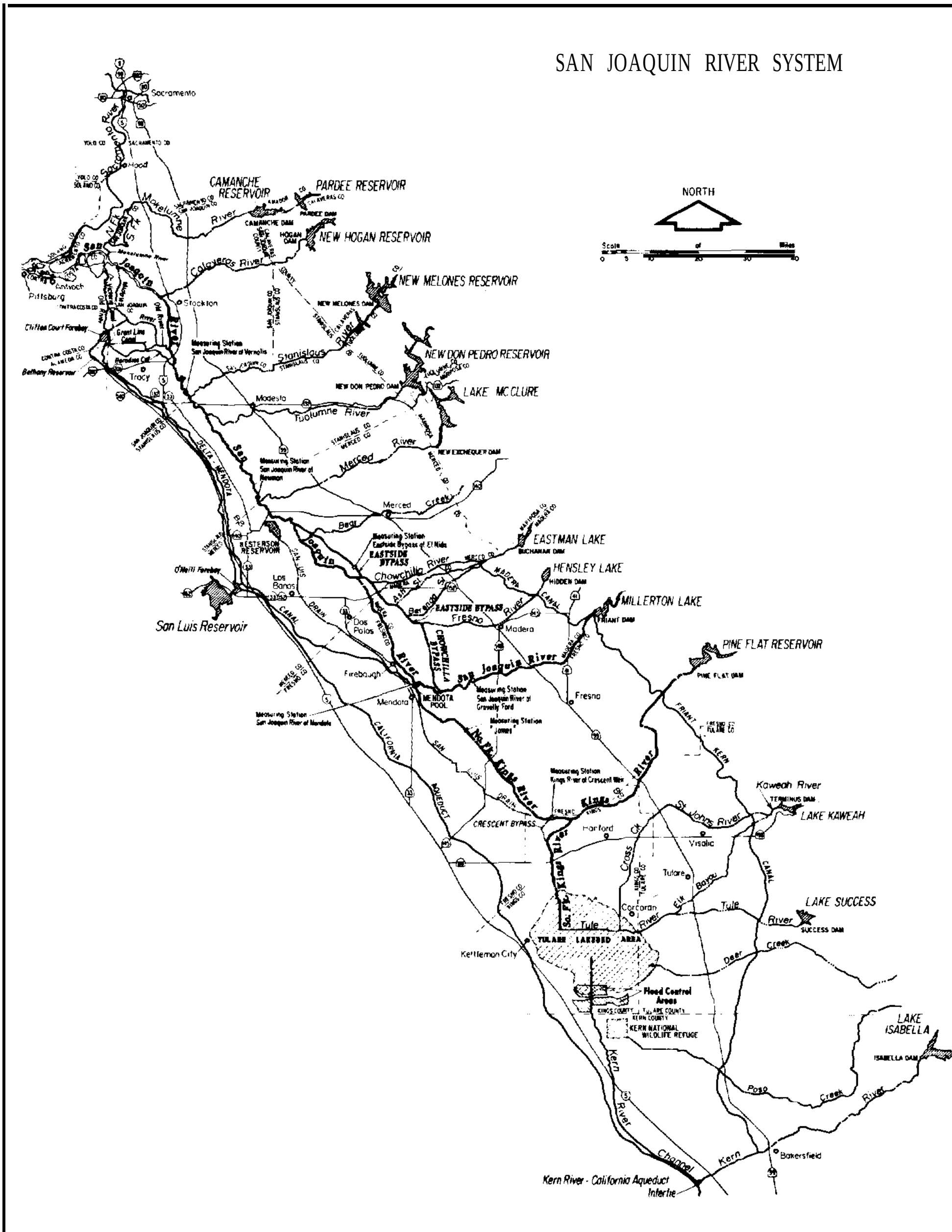

FIGURE 1. San Joaquin Valley, CA, showing principal components of the water supply network

extra water (the leaching fraction) to move the deposited salts away from the root zone. As the water percolates through the soil, it also dissolves native minerals. The result of both actions is an appreciable increase in salt content and a change in the ionic composition and trace mineral content of the leachate.

The exact changes in quality depend on irrigation practices, soil characteristics, and length of time the land has been drained. For example, drainage water collected from individual systems can have total dissolved solids concentrations ranging from less than 2,000 mg/l to more than 100,000 mg/l. Generally, the drainage is less salty in the north,

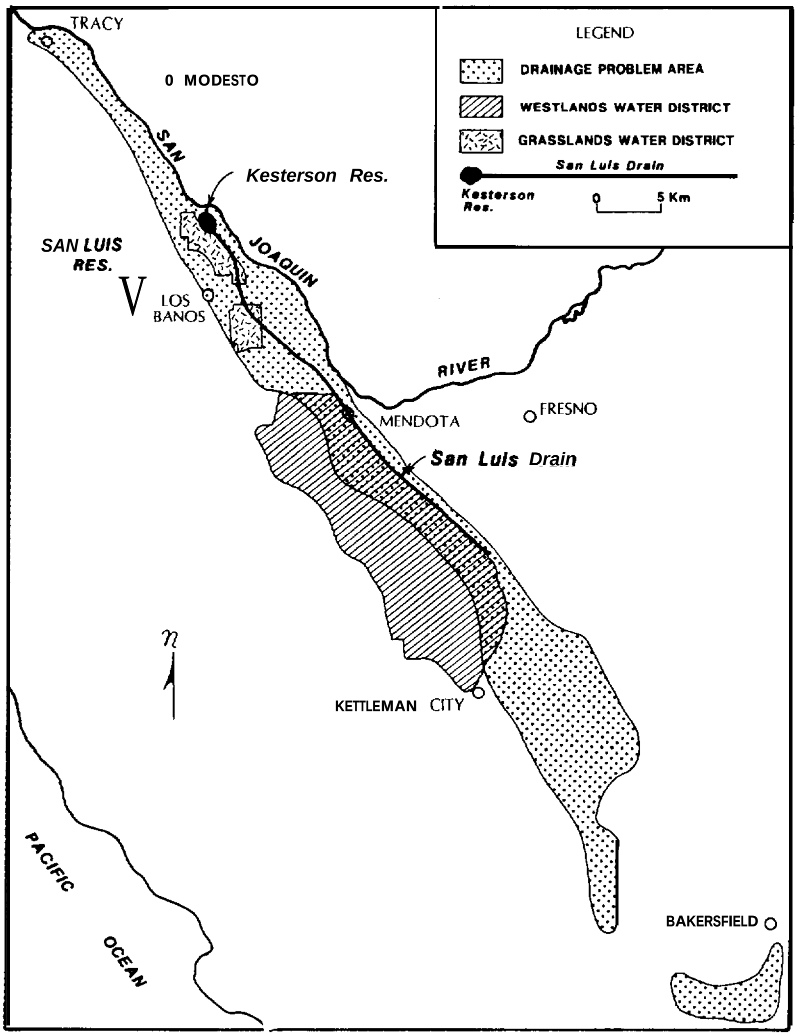

FIGURE 2. Drainage problem area and Kesterson Reservoir, located in the western central portion of the San Joaquin Valley, CA.

moderate in the south (Tulare Lake basin), and highest in the central portion of the valley's west side.[1] Concentrations of nitrate and boron follow the same general pattern.

There have been several attempts to predict the quality of drainage that would result if the effluents from different areas were combined in a single collector system. Four such independent estimates of mineral quality are shown in Table 1. These estimates are for drains that would have been in operation for some time (up to 50 years). Although purely hypothetical, the estimates themselves are in reasonable agreement considering the number of assumptions that were required for the calculations. A few points can be made regarding these predictions.

1. The water is moderately brackish, with a salinity about one fifth that of sea water.
2. The drainage is a sodium sulfate type.
3. Nitrate-nitrogen concentrations are quite high when compared to those found in the applied water. (Nitrate is essentially the only inorganic nitrogen ion present.)
4. Phosphorus occurs in relatively low concentrations as compared to nitrogen.
5. High concentrations of boron, a phytotoxin, are present, which can interfere with reusing drainage in irrigation.

TABLE 1
Comparison of Various Estimates of Steady-State Chemical Composition of Subsurface Drainage from the San Joaquin Valley after Several Years of Operating a Combined Drainage System

Constituent	IDP[a]	DWR[b]	Price[c]	USBR[d]
Calcium and magnesium	6200	380	500	664
Sodium	970	1900	1500	1370
Potassium	5.3	20	20	6
Bicarbonate	350	220	200	350
Sulfate	1750	3500	3000	3279
Chloride	660	1000	1200	826
Boron	10.2	11	10	9
Nitrate-nitrogen	21	20	20	25
Total phosphorus	0.31		0.15	0.10
Total dissolved solids	6200	6800	7000	6600

Note: Concentrations in mg/l.

[a] Interagency Drainage Program (IDP)[2] — projected values for the year 2025.
[b] California Department of Water Resources (DWR)[3] — projected Master Drain after 50 years of operation.
[c] Price[4] — projected for San Luis Drain, 1970.
[d] U.S. Bureau of Reclamation (USBR)[5] — San Luis Drain, 2020 estimated quality.

It must be emphasized that the values in Table 1 are for idealized composite samples — the water from any particular area might be higher or lower than shown. For the central area, for example, average total dissolved concentrations approach 10,000 mg/l, with the concentration of the various ions increasing accordingly.

In addition to common chemicals, drainage water contains appreciable amounts of trace elements. Table 2 lists the ranges of trace elements reported by the State of California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (USBR) for the federal San Luis Drain. This drain collected water from the central portion of the valley's west side, so the data are only representative of this area. The table shows a fairly wide range of trace elements in the drainage. Levels of selenium, strontium, chromium, iron, and nickel are particularly elevated. If the drainage samples analyzed had been from the Tulare Lake basin, arsenic concentrations would be higher (up to 1 mg/l in some drainage systems) and selenium levels would be lower. From a treatment perspective, the important point is that there may be more than one constituent of environmental concern.

Farmers in the west side of the San Joaquin Valley apply over 150 organic chemicals to soils and crops for pest control.[6] In general, these compounds are not found at high concentrations in subsurface drainage, although they are often found in tailwater (surface runoff) from irrigated fields. Even the persistent chlorinated hydrocarbons (such as DDT, dieldrin, and endrin) are decreasing in subsurface drainage (Table 3). The relatively low pesticide concentrations in subsurface drainage are probably due to a combination of degradation (enhanced by long travel time through the soil) and adsorption onto soil particles.

Finally, subsurface drainage has little turbidity and few readily available organic compounds. The water is slightly alkaline as it enters the collector drains and is relatively well buffered by bicarbonate alkalinity.

Exact quantities of drainage from the San Joaquin Valley are difficult to estimate. The Interagency Drainage Program* estimated that drainage yield varied from 0.5 to 1.2 acre-

TABLE 2
Range in Dissolved Trace Element Concentrations (μg/l) in Waters from the San Luis Drain, 1983—1984

Element	Range (μg/l)
Selenium	230—350
Strontium	6400—7200
Iron	150—500
Cadmium	1—20
Chromium	20—36
Copper	IO-20
Lead	1-6
Manganese	10—20
Mercury	0.1—0.2
Nickel	20-60
Silver	
Zinc	10—20

Note: Analysis by the California Department of Water Resources and the U.S. Bureau of Reclamation.

TABLE 3
Concentration of Various Chlorinated Hydrocarbons Detected in Subsurface Agricultural Drainage from California's San Joaquin Valley during the Period 1970—1982

	Maximum concentration (μg/l) in time interval		
Compound	1978-1982	1975-1977	1970-1974
Aldrin	0.01	0.025	0.025
DDD/DDE/DDT	ND[a]	0.17	80
Dieldrin	ND[a]	0.01	25
Endrin	0.01	0.02	3
Toxaphene	ND"	0.54	335
PCBs	ND'	0.19	0.19

[a] Not detectable.

ft/acre (average = 0.8), depending on location and age of the drainage systems. If all problem lands were drained, upwards of 600,000 acre-ft of drainage would be produced annually. Drainage facilities (canals and pipelines) designed to transport combined valley drainage have varied from 300 to 900 ft^3/s capacity, depending on the size of the area being served.

III. DRAINAGE WATER MANAGEMENT

An appreciation of present-day treatment concerns can be obtained from brief summaries of the various drainage management scenarios advanced over the past 40 years and the needs these scenarios were designed to alleviate.

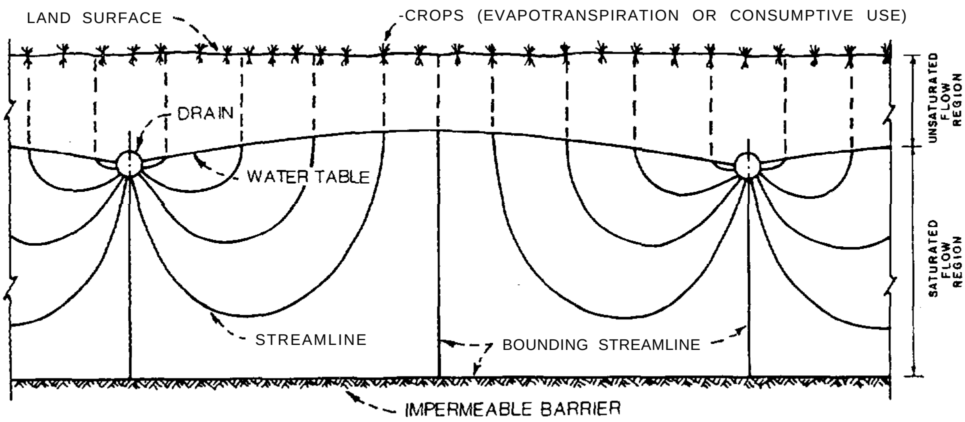

FIGURE 3. Vertical section through a typical agricultural drainage field.

A. SAN LUIS DRAIN — ORIGINAL PLANNING

In the early 1950s, when engineers began planning for delivery of Central Valley Project water to the valley's west side, they knew artificial drainage would be essential to prevent rising water tables downslope of the irrigators and to remove imported salts from the valley. The San Luis interceptor drain (Figure 3) was authorized as a project feature. The drain was to collect water from the federal service area and discharge it to the delta near Antioch. Project planning did not advance to the stage where a detailed analysis of environmental concerns was prepared.

B. SAN JOAQUIN MASTER DRAIN

In the late 1950s, as the State of California began planning to bring irrigation water to the San Joaquin Valley, its engineers and agricultural scientists also recognized the need for drainage facilities. The primary purpose of the proposed facilities was to provide a means for removing as much salt from the valley as was being delivered in irrigation water imported to the valley. A detailed analysis of means for disposing of this water was conducted. Options evaluated included desalting, direct discharge to the ocean, evaporation ponds, and discharge to the delta near Antioch. In the preliminary version of the final report,[3] the recommended project was to combine the state and federal drains (to be called the Master Drain), with discharge to the delta. A report on expected problems' in receiving waters singled out nitrogen and pesticides as constituents of particular concern.

In the late 1960s, the Federal Water Pollution Control Administration (now the Environmental Protection Agency) released a report' describing studies to assess the impact of a delta discharge on receiving water quality. In essence, federal investigators concluded that the high nitrogen levels in the effluent could cause adverse levels of algal growth (eutrophication) in the estuary. They recommended that nitrogen removal be part of any planned discharge. Pesticides were also considered in the analysis, but levels in the drainage were found to be similar to those already present in the delta. Since no particular problems had been identified as being caused by ambient delta concentrations, pesticides were not included as an area of particular concern.

As a result of concerns about potential eutrophication problems in the delta, the DWR, the USBR, and the Federal Water Pollution Control Administration initiated a cooperative 3-year treatment study. Most of the studies were conducted at a DWR field laboratory on the west side of the valley and included investigations of desalting, bacterial denitrification, and algal stripping. Results, as summarized by Brown,' demonstrated that

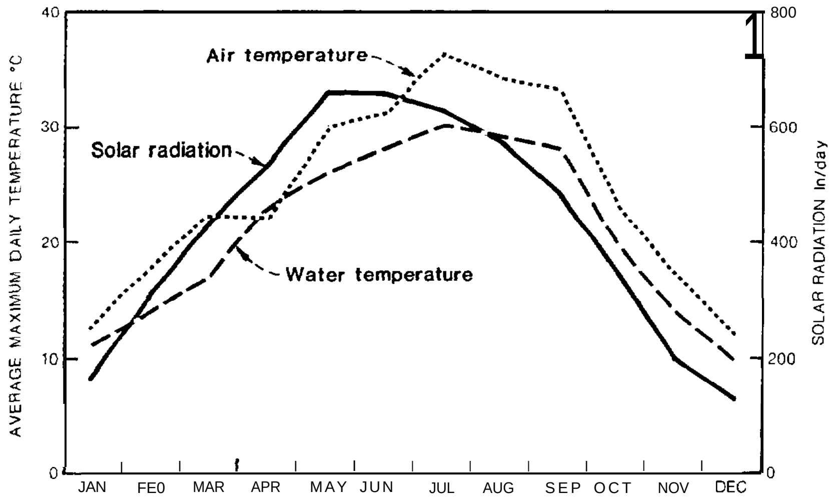

FIGURE 4. Annual cycle of monthly mean solar insolation and air and water temperatures at Firebaugh, central San Joaquin Valley, CA.

1. Desalting by electrodialysis or reverse osmosis could effectively remove salts, but did little to remove boron or nitrate.
2. Bacterial denitrification, using methanol as a carbon source, could be used to lower the nitrate concentration from 20 to about 2 mg/l. Upflow rock reactors seemed to be the most promising container; however, possible hydraulic problems associated with plugging by actively growing bacteria were never completely resolved. Required residence time was in the range of 2 to 4 h, and methanol dosages were about 60 mg/l when nitrate-nitrogen concentrations were 20 mg/l.[10]
3. High densities of algae could be grown in outdoor cultures by using relatively long residence times (5 to 16 d), shallow depths (20 to 40 cm), mixing, and additions of small amounts of phosphorus and iron. Ferric chloride was used as a coagulant to harvest the algal mass. The effluent from the ponds contained about 3 to 5 mg/l total nitrogen, mostly as dissolved and particulate organic nitrogen. The San Joaquin Valley's Mediterranean climate and drainage discharge patterns combined to make the use of outdoor cultures particularly attractive, since the seasonal periods of highest light intensity coincided with periods of maximum drainage volume. Figure 4 illustrates a typical annual cycle of air temperature, solar radiation, and water temperature at a California Irrigation Management Information System site in the central west side of the valley. Figure 5 shows that drainage flows are also generally higher during the months when sunlight and temperature are maximum.

Preliminary cost estimates (1970 dollars) developed for the two biological processes were about \$24/1000 m^3 for the bacterial process and about \$3611000 m^3 for the algal stripping process. The algal process would require about 5000 ha of ponds to treat the estimated flow of the San Joaquin Master Drain." Larger scale desalting studies were needed to work out pretreatment requirements for these processes before cost estimates could be made for the processes.

In 1969, the State of California determined that it could not finance its portion of the Master Drain and withdrew from the project.

C. SAN LUIS DRAIN — INITIAL CONSTRUCTION

To fulfill its continuing obligation to provide drainage facilities, in 1968 the USBR

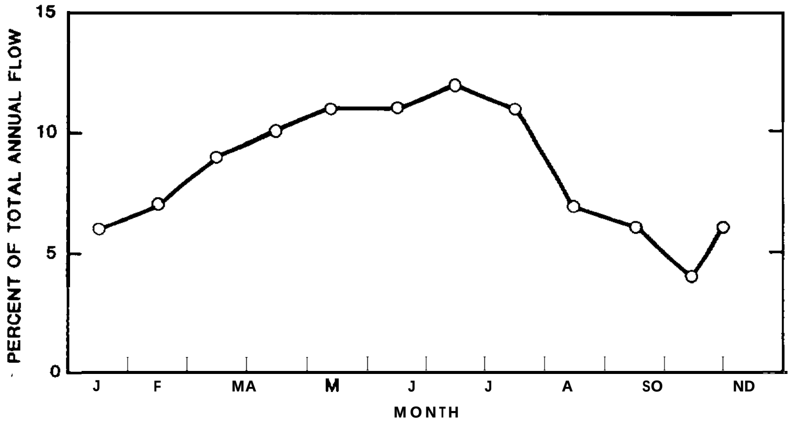

FIGURE 5. Percentage of total annual drainage flow, on a monthly basis, in the federal service area, central San Joaquin Valley, CA.

began construction of the middle 130 km of the 320-km San Luis Drain to the delta. This section of the drain was completed in 1974 and terminated in an interim holding facility, the Kesterson Reservoir. Although over 2000 ha were purchased for the reservoir, only about 500 ha were developed into a series of about 40-ha cells. These cells were surrounded by levees and had an average depth of 1.2 to 1.5 m. They were designed to provide interim storage until completion of the drain to the delta, with some of the storage coming from evaporation losses. The ponds were built more like marshes than true evaporation ponds in that water depth was quite variable.

Environmental concerns related to a delta discharge and to financing caused the USBR to postpone its plans to complete the San Luis Drain. Structural integrity of the concrete drain itself was maintained by keeping it full of good quality water. Similar quality water also was released into Kesterson Reservoir, which promoted the growth of emergent vegetation and helped convert the reservoir to a brackish water marsh. The U.S. Fish and Wildlife Service began to manage the reservoir as part of its Kesterson National Wildlife Refuge to provide additional waterfowl habitats in the San Joaquin Valley.

In the early 1970s, the USBR, with technical assistance from the DWR, continued biological studies of removing nitrogen from subsurface drainage.[12] The main area of investigation was the so-called "symbiotic" process, where a combination of algal and bacterial pathways was used to remove nitrogen. The plants (either algae or higher aquatic plants) incorporated some of the dissolved nitrogen into their cells. Far more importantly, the plants also provided an organic carbon source for bacterial denitrification. Although it was difficult to demonstrate conclusively, bacterial denitrification apparently occurred in microlayers at the pond bottom or in decomposing plant mass and was the major pathway by which inflowing nitrogen was removed from drainage water. The symbiotic process appeared technically feasible in that about 90% nitrogen removal was obtained. It was also economically attractive because neither mixing nor an outside organic carbon source was required. As a sidelight, it was found that periphytic diatoms attached to higher aquatic plants (or an inert substrate such as dead tumbleweeds) effected considerable silicon removal. Silicon can cause scaling when drainage is used in power-plant cooling or in desalting plants. Ponds of alkali bullrush were subsequently tested for their potential in pretreating drainage going to a demonstration-scale reverse osmosis desalting facility and were shown to be effective at removing silicon.

D. INTERAGENCY DRAINAGE PROGRAM (THREE-AGENCY)

In 1975, the USBR, DWR, and the State Water Resources Control Board formed the

Interagency Drainage Program (IDP) in another attempt to find an environmentally acceptable and cost-effective means to resolve the valley’s drainage problem.

Much of the work was developed around the principles and standards of the Water Resources Council.“’ The goal was to develop separate environmental and economic plans and then merge the two into a recommended plan. The final plan[2] was a valley drain with discharge to the western delta at Chipps Island. Unlike the San Joaquin Master Drain, the IDP drain included several thousand hectares of waterfowl habitat (marshes) and regulating reservoirs. The California Department of Fish and Game and the U.S. Fish and Wildlife Service participated in the program and endorsed the recommended plan.

With respect to problem chemical constituents, mathematical modeling indicated that a delta discharge would cause only local increases in dissolved nitrogen and algal growth. Thus, the plan did not include nitrogen removal requirements, but did indicate that nitrogen removal might be needed if the actual discharge caused unacceptable increases in algal growth in the estuary. Arsenic from Kern County was listed as a concern; however, source control appeared to be the most likely option for avoiding receiving water problems.

In his comments on the plan’s environmental impact report, Dr. Ray Krone, a consultant for the Contra Costa Water District, pointed out that selenium might also be a trace constituent of concern. Dr. Krone, from the University of California, Davis, was concerned that selenium levels might be elevated in subsurface drainage. These concerns were based on high selenium concentrations in some groundwater near Davis and the possibility that similar selenium-rich formations existed further down the valley.

There were no formal treatment studies underway during the late 1970s, although the DWR and the faculty and staff from the aquaculture program at the University of California, Davis, investigated the potential use of agricultural drainage as a culture medium for growing economically important invertebrates and fish. As reported by Monaco et al.,[14] most of the species tested did well in the drainage. Exceptions were the Asiatic clam and the Pacific crayfish, but the data were not adequate to determine the causes of the problems to these animals. During this period, Oswald’” made an extensive analysis of projected changes in water quality as the water passed through the marshes, regulating reservoirs, and canals of the IDP’s recommended plan. Oswald’s report provides much useful information on environmental conditions in the San Joaquin Valley as they relate to the potential for outdoor treatment systems.

The IDP plan, like the Master Drain, could not be financed by the valley agricultural community, and it was not constructed. As with the Master Drain and the San Luis Drain, there was considerable adverse reaction from agencies, organizations, and individuals around the bay-delta regarding an estuary discharge. In addition, Tulare Lake basin farmers did not actively support the plan, choosing to rely instead on construction of in-valley evaporation ponds.

E. SAN LUIS DRAIN — REPORT OF WASTE DISCHARGE

As before, the USBR still had the legal obligation to alleviate and prevent drainage problems in its water service area. In the late 1970s, tile drainage systems from about the first 20,000 ha provided with collector systems were connected to the San Luis Drain, and by 1981 the entire flow in the drain was from subsurface drainage. The drainage water flowed into Kesterson Reservoir. Thus, for the first time the marsh plants and wildlife were exposed to actual drainage water, with all its potential problem constituents.

In 1980, the USBR began active planning to complete the San Luis Drain to the western delta near Chipps Island. Preparation began on an environmental impact document and a report of waste discharge (as required by the National Pollution Discharge Elimination System).

Both documents had gone through several drafts when the U.S. Fish and Wildlife Service began to express concerns that drainage water was causing waterfowl deaths and deformities at Kesterson Reservoir. Preliminary indications were that selenium, found at concentrations of 300 to 400 μg/l in San Luis drainage water, was the element responsible for water fowl problems.[16] These findings prompted the State Water Resources Control Board to issue Order WQ 85-1, calling for plugging the collector lines conveying drainage to the San Luis Drain (and Kesterson) and the cleanup of Kesterson Reservoir. Planning for a delta discharge was also halted pending resolution of new environmental issues resulting from the Kesterson findings.

F. INTERAGENCY DRAINAGE PROGRAM (FIVE-AGENCY)

In 1984, three federal agencies (U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, and U.S. Geological Survey) and two state agencies (California Departments of Water Resources and Fish and Game) formed a second Interagency Drainage Program. The general objective of providing an environmentally sound and economically feasible solution to the valley's drainage problems remained unchanged. However, the emotional and technical issues related to selenium had dramatically changed the range of options available to the planners and regulatory agencies. Selenium is found in widely varying concentrations in valley drainage and appears to be leaching from natural shales in the alluvial fans (and interfans) on the valley's west side. Possible bioaccumulation and biomagnification of selenium through the food web complicates the task of setting water quality standards for this element.

The five-agency drainage program includes research by the U.S. Geological Survey on the chemical composition of drainage from various areas in the valley and research by the U.S. Fish and Wildlife Service on effects of selenium and other trace elements on fish and wildlife. Planning focuses on local solutions to drainage problems, including evaluation of possible land retirements in the major problem areas, treatment to remove problem constituents, and more efficient use of drainage water to reduce effluent quantity. Discharge to the ocean, either directly or via the San Joaquin River or the delta, is not politically possible at this time.

IV. SUMMARY AND DISCUSSION

The drainage problem has been around for some time, as has the perceived need to remove something from the water to make discharge of the water to a salt sink (such as the ocean) environmentally acceptable. This "something" has varied from total salts to nitrogen to pesticides to various trace elements, including selenium. As part of its Order WQ 85-1, the State Water Resources Control Board" established interim standards for the San Joaquin River for total salts, boron, selenium, and molybdenum. The interim selenium objective of 5 μg/l will likely drop to 2 μg/l after a few years.

Similar standards or objectives for the delta or evaporation ponds have not been adopted. Evaporation ponds are, however, subject to provisions of the California Administrative Code, which defines the levels of particular elements that cause the ponds to be classified as toxic waste pits. In the case of selenium, the ponds become toxic waste pits when concentrations exceed 1 mg/l. Ponds that exceed these values (and there are already a few in the valley) must be closed or double-lined to prevent leakage from ponds. The California Department of Fish and Game is also considering imposing waterfowl hazing programs on ponds containing selenium to minimize the birds' exposure to potential toxic contaminants.

In the Grasslands Water District (Figure 2), duck club managers have long used subsurface drainage as an important part of their water supply. The blended drainage water, which was moderately high in selenium (in the 50 to 100 μg/l range), flowed through the marshes and out to the San Joaquin River. Marsh vegetation and bacteria acted as a biological treatment system and removed much of the selenium as the water passed through the system.

As a result of Order WQ 85-l and concerns associated with elevated selenium levels in waterfowl, the duck clubs no longer take drainage water. The water now goes directly to the San Joaquin River, and treatment may be required to meet the new water quality objectives established for the river.

Publicity over the Kesterson findings and concern over the possibility of similar problems with wildlife refuges receiving return flows from agriculture and other sources has resulted in the so-called "westwide study". In this study, the U.S. Geological Survey and U.S. Fish and Wildlife Service are conducting reconnaissance-level studies to determine if selenium or other trace elements are causing problems in other refuges throughout the West. In California, the Salton Sea and the Tulare Lake basin are included in the study program, and preliminary results have shown elevated selenium levels in biota from these two areas.

Various studies have demonstrated that it is technically feasible to remove salts, nitrogen, and boron from drainage water. Studies underway now also indicate that selenium can be removed by physical, chemical, or biological processes. The challenge is to provide processes that result in an environmentally safe effluent (i.e., remove selenium as well as other toxic substances), that do not result in residues that also cause problems, and that farmers can afford. We are optimistic that continued scientific research and technology development will help meet this challenge.

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