Innovation in Salinity Management: The California Experience

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Major irrigation projects in California have provided surface irrigation water supplies to arid and semi-arid lands and allowed them to be converted to highly productive farms. However, there are numerous worldwide historical examples of irrigation projects that have contributed to salinity so this factor is a concern. The Imperial and the western San Joaquin Valleys are areas in California that have been provided irrigation water leading to salinity issues. In both cases, irrigation causes the water table to rise, requiring the installation of subsurface drainage systems to keep the root zone free of excess water and salt. Appropriate drainage water disposal is the main problem, and on this point, dramatic differences exist between the two valleys. This report describes the situation in each valley followed by a statement on the similarities and contrasts between the valleys.

The Imperial Valley

The Imperial Valley is located in southeast California immediately north of the Mexico border. Millions of years ago, the Gulf of California extended northward from its present boundary covering the present Imperial Valley to a northern point near Indio, California (Figure 1). The Colorado River flowed into the Gulf near the present California-Mexico border, close to Yuma, Arizona. Sediments in the Colorado River derived from carving the Grand Canyon and other sources were deposited in the Gulf producing a berm. Eventually, the berm separated the north

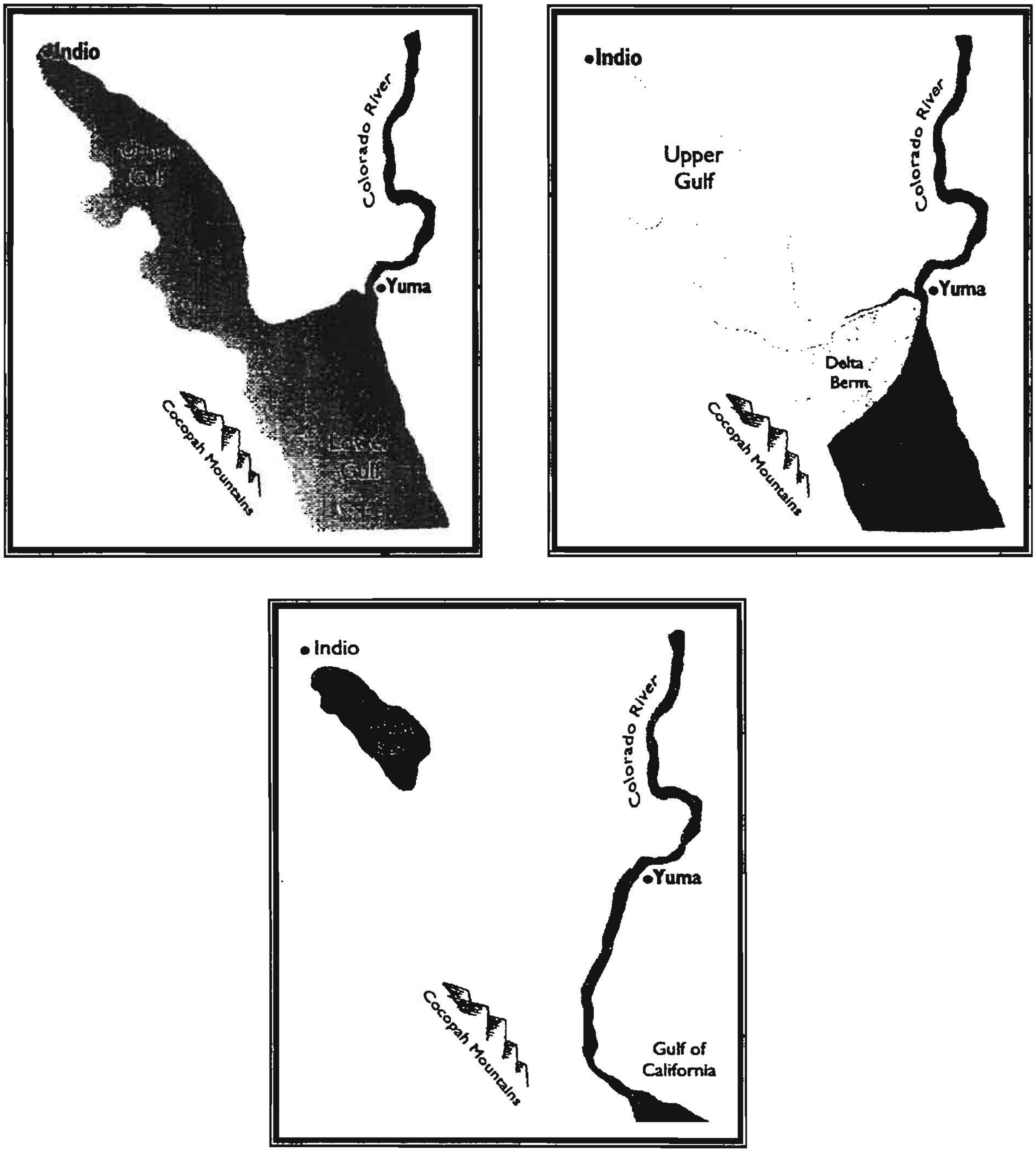

Figure 1. Evolution of the Salton Sea.

section of the Gulf from the main Gulf. The main Gulf was pushed further and further south as sediments continued to be deposited. The river flow changed course depending upon sediment deposits–flowing sometimes south to the Gulf and sometimes north to the Salton Basin. As the river changed course, sediments were deposited on both sides of the berm building up the land area. Without a continual flow of water, the upper gulf dried.

The Imperial Valley is located in the Salton Basin and has a hot, desert climate allowing agricultural productivity year-round. Very little precipitation occurs and the evapotranspiration rate is high. Diversion of irrigation water through a series of canals from the Colorado River has converted the desert to a highly productive agricultural industry. Irrigation began in earnest in 1901. The rudimentary canal system clogged with silt restricting water deliveries at critical times causing crop failure. After dredging proved inadequate, the engineers gambled that a new location of the temporary diversion could be secured before the summer's high water. Exceptionally high river flows broke through the new intake and the entire river flowed northward into the Salton Basin for several months before the Colorado River could be turned back into its bed. The river flowed to the lowest elevation where it formed the present day Salton Sea. This event did not deter the development of irrigated agriculture very long. A very elaborate system of irrigation canals and drainage facilities have been installed which provide the framework for a highly productive agricultural industry.

Although the original flood flows would have evaporated years ago, the sea has been maintained by agriculture return water flows, sewage, and other sources of water. Approximately 85% of the present inflows are from agriculture. The steady-state balance between evaporation and inflows dictates surface area and therefore the elevation of the sea.

The installation of subsurface drainage systems to complement the irrigation project has provided the means for managing soil salinity and water table elevations to acceptable levels. The opportunity to discharge the drainage water to the Salton Sea has facilitated the sustainability of agricultural production. The Salton Sea and agricultural production are inseparably connected. Agriculture requires a disposal site for drainage water and the Salton Sea requires a supply of water to avoid becoming dry. The inter-linkage between the Salton Sea and agriculture means that each is impacted by decisions made relative to the other. Therefore, issues related to the Salton Sea are major factors in the future of agriculture in the Imperial Valley.

The two critical features associated with the Salton Sea are that 1) with no outlet, the salinity continuously increases as the water evaporates and 2) the sea serves as an important link on the Pacific flyway, North America's west coast route for migrating birds. Over 400 bird species may be found in the locale and the numbers of individuals totals millions at certain times.

In recent years, massive bird and fish die-offs have plagued the sea. Since 1992, hundreds of thousands of birds have died at the Salton Sea. For example, in the first four months of 1998, approximately 17,000, representing about 70 species, died from a variety of diseases. The fish deaths are generally associated with oxygen depletion, which is caused by high levels of nutrients in the sea. So although the salinity of the sea has been rising and is presently approximately 25% more concentrated than the ocean, salinity has contributed little, if any, to the previous fish and bird deaths. Nevertheless, if salinity is allowed to increase, it will eventually be too concentrated to support fish, with subsequent impact on the fish-eating birds.

Considerable public and political attention has been directed toward "saving the sea". The Federal Salton Sea Reclamation Act of 1998 established a structure for determining the kind of project necessary to achieve restoration of the sea. The five characteristics most frequently identified as components of a "saved" Salton Sea are: 1) continued use as an agricultural sump; 2) stabilization of the elevation; 3) control of salinity levels; 4) elimination of preventable fish and bird deaths; and 5) enhancement of water-based recreational activities, particularly sport fishing. To some extent, some of these components are mutually exclusive. Of the five components, the primary focus has been directed on stabilizing the salinity.

The issue extends well beyond agriculture and the Salton Sea. California shares water from the Colorado River with six other states and Mexico. California has been diverting more water than its share because the other states were not fully utilizing their entitlements. That situation has changed and California must, in the next few years, reduce its diversions to its allocated share. Concurrently, there is a growing urban population demanding more water in southern California. A portion of the urban water supply has been from the Colorado River. With decreasing Colorado River water supplies and increasing urban demand, there is a proposal to transfer water from farmers in the Imperial Valley to San Diego with farmers receiving compensation for the water.

Approximately 35% of the water diverted for agriculture ultimately flows to the sea. Most of this is surface runoff and canal spillage, with only 10-12% being subsurface drainage waters. Capturing and using surface flows for irrigation would provide water for transfer to the city. However, this practice would also result in lower, more saline water flows to the Salton Sea, which would accelerate the rate of salinization as well as decrease the sea size. As a consequence, dry sea sediment would be exposed, subject to wind erosion. The time when the salinity would be too high for fish would be sooner and this has significant impact on the fish-eating birds that utilize the sea.

Clearly the issue in the Imperial Valley goes well beyond the well-established principles of soil salinity management under irrigated agriculture. The issue is enmeshed with water quantity and quality matters intertwined with human and wildlife populations that have national and international implications. No accepted resolution to the issue has been achieved at the time of this writing.

The western San Joaquin Valley

The San Joaquin Valley averages 50 miles in width, to encompass 8.5 million acres of valley floor, flanked by the lofty Sierra Nevada Mountains to the east and low-lying coast range to the west (Figure 2). During geologic times, the portion of the earth's crust immediately west of the Sierra Nevada Mountains was beneath the Pacific Ocean at a gradual westward slope. A shallow-water coastal marine basin formed in which thick layers of sediments could accumulate. About 60 million years ago, the gently sloping marine basin was permanently uplifted, creating the present coastal ranges. The trough between Sierra Nevada and the newly emergent coastal ranges became the San Joaquin Valley.

Material eroded from the slopes of both elevated landmasses was deposited on the valley floor. The alluvial plains created from these erosional deposits converged at the valley trough giving today's San Joaquin Valley a smooth, flat appearance. Alluvium on the valley's east side derives from the granitic rocks of the Sierra Nevada Mountains. In contrast, the finer-textured west side alluvium that derives from the sedimentary coast range deposits contains significant quantities of soluble mineral salts and trace elements. Most of the undesirable characteristics associated with the western San Joaquin Valley soils (the area under consideration) are directly due to their origin from marine sedimentary parent material of the coast ranges.

The valley floor appears to be nearly flat but it does have a gradual east-west slope from the Sierra Nevada on the east and coastal range on the west to a low-lying trough. Lengthwise, it slopes gradually to the northwest in a low, broad, and indistinctive divide that interrupts the valley's lengthwise slope at about midpoint. The divide separates the valley into two hydrologic basins. The San Joaquin basin in the north drains to the ocean by the San Joaquin River, the Delta, and San Francisco Bay. The Tulare basin in the south has no natural outlet to the ocean. The major geographic features are illustrated in Figure 2.

A generalized geohydrological cross section is illustrated in Figure 3. This cross section represents a transect in Westlands Water District indicated by a dashed line in Figure 2. Two key features are the low permeable Corcoran clay that separates the underlying confined aquifer

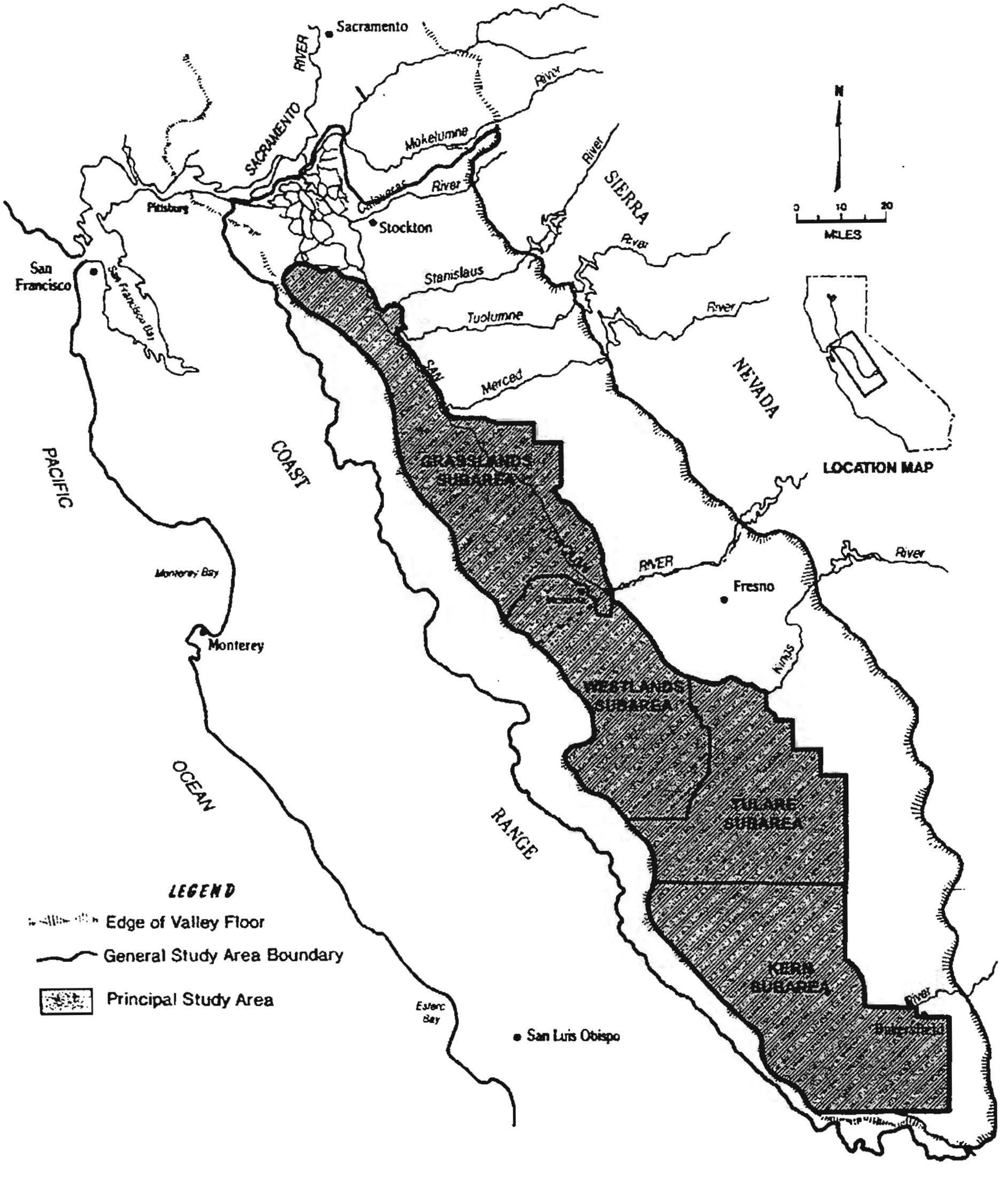

Figure 2. Geographic features of the San Joaquin Valley of California.

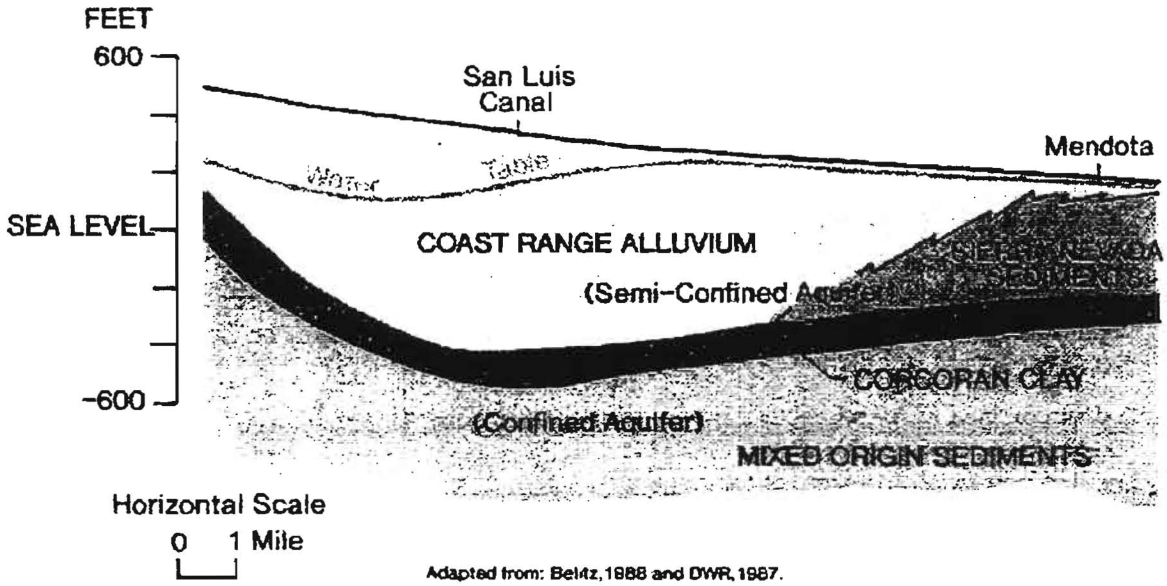

Figure 3. Generalized Geohydrological cross-section in the San Joaquin and Tulare basins.

from the semi-confined aquifer above. Also the water table is hundreds of feet above the confining Corcoran clay, and the alluvium in that zone is highly stratified.

Precipitation in the valley is restricted to the winter months and is inadequate to sustain crop production through the summer. The Central Valley Project (CVP) was first proposed in the 1930's as a massive California project to construct dams, canals, drains, and other structures to provide irrigation water to achieve high agricultural productivity. California had originally planned to construct the CVP but during the depression the state could not raise bond moneys and the federal government assumed management and assigned the responsibility to the United States Bureau of Reclamation (USBR). The need for drainage systems was acknowledged for the lower elevations and the delta to the north was considered as the most likely site for drain water disposal. When initial bids for the project did not include any drainage features, down-slope landowners sought an injunction to prevent the construction. They argued that providing water without drainage would injure their lands, but the suit was dismissed because the USBR was showing good faith in planning the drain. The court stipulated that if plans were not carried out the plaintiffs could again file suit.

Water contractors in the southern part of the valley concluded that at least for the foreseeable future it would be more cost effective for them to use evaporation ponds to dispose of drainage water than to participate in the valley-long drainage canal carrying waters to the delta. Agricultural drainage waters from the northern sector of the valley were to be collected and allowed to flow through a concrete lined canal and eventually discharge near Chipps Island in Suisun Bay east of San Francisco. An 82-mile segment of the drain was completed in 1975 terminating at Kesterson Reservoir. Kesterson Reservoir was to serve the dual purposes of being a regulating reservoir and wildlife refuge. Completion of the second segment of the drain to the bay was delayed pending environmental impact analysis of discharging water into the Suisun Bay.

By 1981, Kesterson Reservoir inflows consisted exclusively of subsurface agriculture drainage from systems installed in the Westlands Water District. Although additional lands had sufficiently high water tables to justify the installation of more drainage systems, the USBR imposed a moratorium on additional farm drainage connections to the drain because of limited capacity of Kesterson Reservoir. This condition was considered temporary because approval and construction of the drain to the bay was expected to be forthcoming.

That expectation was dashed by unanticipated observations and findings. Field observations by the US Fish and Wildlife Service at the reservoir made in the spring of 1983 revealed a very high incidence of mortalities and deformities amongst the newborn birds. About 20% of the observed nests had deformed birds. Deformities included chicks with no eyes, no legs, or no wings, deformed legs, wings, or backs and swollen heads. Approximately 40% of the eggs contained dead embryos. Tissue analysis revealed that selenium concentrations were several times higher than found in waterfowl elsewhere and was identified as the causative factor for damage.

In 1985, the Secretary of the Interior ordered the discharge of subsurface drainage to Kesterson Reservoir be halted. Kesterson Reservoir was closed and drainage service to Westlands Water District discontinued. Subsequently, three federal agencies and two California resources agencies jointly established a San Joaquin Valley Drainage Program (SJVDP) in 1984. The goal of the program was to develop short- and long-range plans for solving the salinity-toxics-drainage problems of the western San Joaquin Valley.

Constraints were placed on the development of the plans. Specifically, all alternative plans must meet California's water-quality objectives and focus on in-valley solutions. The latter constraint eliminated the option of completing the drain as originally planned or any other disposal to a bay or the ocean. A National Research Council committee that reviewed developments and provided technical advice expressed strong dissatisfaction with the political influences that directed SJVDP to look for only in-valley solutions. They stated, "This constraint is not scientifically based." The criticism of the constraint was not based on the belief that out-of-valley discharge was necessarily superior to in-valley disposal, but simply that the option deserved scientific and economic scrutiny.

Selenium, which can bioconcentrate to harmful levels for fish and wildlife, is the major constraint to establishing management practices that would assure sustainable agricultural production. With the absence of selenium, the original plan to complete a canal to carry and discharge agricultural drainage water into the bay would have been completed. Water and salt balance on the agricultural fields could have been balanced providing a stable agricultural system.

History has recorded several major occurrences of salinity and its effects on society, but the earliest and perhaps most serious occurred during 2400-1700 bc in ancient Mesopotamia, now southern Iraq (Jacobsen and Adams, 1958). However, selenium was not an issue in these historical events. Thus, the establishment of appropriate management practices to sustain agriculture in the western San Joaquin Valley is challenged by a new and unique set of circumstances that do not have historical precedence. The need for innovative approaches to managing the problem becomes apparent.

Several management options have been proposed to deal with the salinity-toxics-drainage problem in the San Joaquin Valley. None is singularly adequate, but each may contribute to the solution depending somewhat upon the locale. The management options considered for dealing with the salinity-toxics-drainage problem are 1) source control, 2) drainage water reuse, 3) evaporation ponds, 4) water treatment, 5) land retirement, 6) groundwater management, and 7) discharge to the San Joaquin River.

Source control means reducing the amount of deep percolation below the root zone that must be removed in a subsurface drainage system. Source control requires the farmer to apply water uniformly across the field and accurately control the volume applied. Both of these goals can more easily be accomplished by switching from surface irrigation to sprinklers or micro irrigation systems. Although the amount of drainage water can be reduced, it cannot be eliminated. Some leaching is required to maintain salt balance in the root system. Also, no irrigation system completely applies water uniformly across the field. For non-uniform irrigation, there is a tradeoff between having some parts of the field over-irrigated and other parts being under-irrigated for high crop yield.

The salty drainage water can be used to irrigate salt-tolerant crops. Although the salinity of the drainage water varies somewhat by locale, the electrical conductivity of the drainage water is typically in the range of 8-10 dS m^{-1}. This concentration is higher than would be expected based upon the salinity of the irrigation water and leaching fraction usually imposed in the farming system. This high concentration of salts is the result of flushing out salts that were associated with the original marine environment of the sediments. Furthermore, the drainage water contains significant concentrations of selenium, boron, and other minerals associated with marine environments. The amount of salt removed in the drainage water is greater than the amount of salt added with the irrigation water.

Although selenium generally does not impair drainage water for irrigation, the total salt concentration and boron do. Nevertheless, by selecting very salt tolerant crops and/or blending drainage waters to reduce their salinity, they can be used for irrigation. This practice reintroduces the salts to the groundwater system because leaching of salts to maintain salt balance in the root zone is required. Thus, additional drainage water is generated that still must be disposed, albeit the volume has been reduced through reuse.

The only way to sustain agriculture production is to separate salts from productive agricultural lands. Evaporation ponds are an option that permanently removes salts from productive farmland and accumulates them on land selected for a pond. Long-term removal of the salts is another issue that still must be resolved. Unfortunately, selenium in the water creates a significant bird hazard. Therefore, the concentration of selenium in the drainage water is a significant factor in the feasibility of using this option. In general, the selenium concentrations in the drainage waters from the Tulare and Kern subareas are generally lower than for Westlands and some parts of Grasslands. The number of operating evaporation ponds in the Tulare/Kern subarea have declined form 24 in 1990 to 7 in 1998. The reduction, in part, is a result of the operating costs associated with modifications to evaporations ponds, construction of compensation and/or alternative wetland habitat, and water quality and biological monitoring requirements for compliance with waste discharge requirements into the ponds.

All previously constructed evaporation ponds in the Westlands Water District have been closed. The severe bird hazard is one factor, but the Toxics Pit Act also dictates against evaporation ponds. The Toxics Pit Act was passed to protect groundwater from toxic chemicals. Liquids classified as a toxic waste cannot be imponded without very expensive lining requirements. Some years ago, the decision was made to classify a water with 1 mg L^{-1} of selenium as a toxic waste. The concentrations of selenium in the drainage water in the Westlands area, after some concentration through evaporation, can exceed the "toxic" criteria and be subject to expensive lining in addition to costs for mitigating bird damage.

Evaporation ponds have free standing water that attracts birds. As an alternative, evaporator ponds have been proposed. An evaporator pond is defined as one where water is discharged at a rate that does not exceed the evaporation rate, and thereby avoids ponding which attracts birds. A major problem is that the temperol drainage water production does not match the temperol evaporation rate. Designing the pond requires accommodating temperol variations and may require a storage facility. An additional problem is that rainfall may collect in the evaporator pond, creating a short-term ponding condition that attracts birds.

Water can be treated to reduce total salinity and selenium. Reverse osmosis (RO) is the most promising treatment technology, but is constrained by the high cost and difficulties with safe disposal of the brine. The value of the treated water could offset some of the treatment costs and a water trade with the urban sector, which can afford to pay more for water, could enhance the feasibility of RO treatments. Treating drainage water to remove only selenium would still leave a very saline water. Nevertheless, it would increase the options for disposing the drainage water with less ecological damage. Under proper conditions, selenium can be volatilized and/or reduced to elemental form. Selenium concentrations are reduced in open systems such as flowing through wetlands but this solution could pose hazards to wildlife. Forcing water to flow through a series of straw bales in a channel has been demonstrated to greatly reduce the selenium concentration in the water. Other treatment technologies are available but none has yet reached the stage of being incorporated into an operational system.

Groundwater management entails increased pumping for irrigation to lower the water table and reduce drainage volume. The water in the confined aquifer and in the lower zones of the semi-confined aquifer (Figure 3), is pure enough to be used. During drought years, farmers have pumped more to compensate for reduced surface water supplies and in turn lowered water tables. In principle, this practice could be continued during years of plentiful surface water supplies, however its success requires coordinated regional management and compliance. A long-term consequence is that pumping accelerates the exploitation of high quality groundwater. Rather than discharging salts and chemicals through drainage systems, the chemicals move downward with the water toward the zone from which the water is pumped. Pumping increases the rate at which good quality water is replaced by poor quality water.

Taking land out of agricultural production and stopping irrigation would reduce the drainage volumes. As a voluntary program, growers with high water tables and low agricultural productivity would be the most likely to agree to retire their lands. These farms are likely to be located in the lower elevations, near the trough of the west side, which could receive lateral flows from the upslope irrigation. A negative consequence is, with a high water table, water might migrate to the soil surface by capillary action transporting and depositing salts and toxic elements at the soil surface. The resulting landscape would be sparsely vegetated, promoting erosion and degrading wildlife habitat. However, without a drainage system, the productivity of the farms will progressively decrease and reach non-economical levels. This would result in a forced land retirement.

Surface waters flow naturally in the Grasslands area to the San Joaquin River. The agricultural area is separated form the river by zone of wildlife habitat, including duck ponds. Historically, drainage waters were commingled with surface waters and allowed to flow through wildlife habitat to the San Joaquin River. Some was used to irrigate land to provide vegetation for birds. With the event of Kesterson Reservoir, free flow of drainage waters to the San Joaquin River was stopped. An agreement has been achieved to allow some drainage water to be discharged to the San Joaquin River with specific load limits for selenium. The load limit for selenium released to the river decreases annually. Therefore, the constraints to managing drainage waters in the Grasslands area increases with time and the districts have imposed a combination of management options to cope with the situation.

The development of an Integrated Farm Drainage Management (IFDM) plan is an innovative approach for dealing with the salinity-toxics-drainage problem. As originally proposed, the farm would be divided into various sectors. The first sector would be irrigated with good quality water and planted to salt-sensitive crops. Drainage water from the first sector would be used to irrigate salt tolerant crops in a second sector. Drainage water from this sector would be used to irrigate halophytes. Finally, drainage water from the halophytes would be disposed of in an evaporator pond. As water moves through the system, the drainage water becomes increasingly concentrated and the volume of water for ultimate disposal is reduced. Various pertubations of this system are possible, but the main concept is that it incorporates a combination of management options into the management scheme. The optimal combination of options would be established by economic analyses.

A farm was established to demonstrate the IFDM concept. The original design did not adequately accommodate for all the drainage water and there have been a series of modifications to the system over the years. The "perfect" system has not yet been demonstrated, but the concept has merit and has attracted interest including other farms instituting various versions of the system.

Comparison of the Two Valleys

Historically and scientifically two basic principles for sustained irrigated agriculture have been established. 1) Salt balance, defined as salts removed must equal salts added, must be achieved in the crop root zone, and 2) drainage systems must be installed and drainage water containing dissolved salts removed when the water table reaches the root zone. In the absence of wildlife impacts, these principles were adhered to in each valley. In the Imperial Valley, salt balance was achieved by installing drainage systems and discharging the drainage water into the Salton Sea. In the western San Joaquin Valley, a program to adhere to these basic principles was initiated to collect drainage waters and convey them to the bay. In both cases, adherence to these basic principles has not been adequate because of wildlife considerations.

With regard to wildlife, the two cases differ dramatically. In the Imperial Valley, it is the increased salt concentration in the Salton Sea, which will eventually kill fish and impact the fish eating birds that utilize the sea during their seasonal migration. The western San Joaquin Valley is plagued by selenium in the drainage water that impacts fish and wildlife at low concentrations no matter where the water goes. The seriousness of the problem varies somewhat by location within the valley. All areas are impacted however and sustainability requires implementing a combination of all the options which can partially mitigate damage.

Politically, the farmers in the western San Joaquin Valley are isolated from the urban sector. With adequate food supplies, the urban sector does not appreciate the value of sustained agricultural productivity in the valley but are sensitive to harm to the environment. Indeed, land retirement is the favored option frequently expressed by representatives of the urban and environmental communities.

The interaction among the agricultural, urban, and environmental communities in the Imperial Valley is more complex. The Salton Sea depends upon agricultural waters to exist and farmers depend on the Salton Sea to deposit drain water. With water supply shortage, the urban communities can benefit from some of the water that is flowing to the Salton Sea.

A new paradigm

The future of both agriculture and wildlife in the Imperial and western San Joaquin Valleys can be enhanced by a cooperative rather than an adversarial approach by agricultural and environmental advocates. Regulations will drive the future of agriculture on the west side. A policy directed towards increasing bird populations through compensation habitat and other means while allowing some bird damage would enable growers to use a combination of drainage-disposal methods to sustain agriculture. In the Imperial Valley, agriculture drainage waters could be used to create productive wildlife habitat prior to discharge into the Salton Sea. Drainage waters can sustain wildlife before terminating at the Sea where the chemicals accumulate and concentrate to very high levels. Indeed, high numbers of birds are presently observed in areas adjacent to the Sea's main body. The productivity of the adjacent areas could be increased by creative design and construction of wetlands specific for the purpose of accommodating the wildlife that frequents the area. This approach has been recommended by the UC MEXUS Salton Sea Project Steering Committee (UC MEXUS, 1999) and the Pacific Institute (Cohen, et al. 1999).

In the western San Joaquin Valley, growers can create a productive wildlife system by mitigating evaporation pond damage and constructing productive alternative and compensation habitats. The feasibility of constructing highly productive bird habitat has been verified by a study done by the Tulare Lake Drainage District. A 307-acre wetland habitat was designed and constructed specifically to provide foraging and nesting habitats for American avocet and black-necked stilt. During the 1995-2001 monitoring period, annual nesting starts averaged 3,003 (range of 1,793 to 4,102). By comparison, the 2900-acre evaporation ponds had 2,260 nest starts in 1994 before the compensation habitat was built and the number decreased to 1,240 in 1995 and 190 in 1996 and remained low in recent years.

A new paradigm is required whereby wildlife habitat is not limited to "natural" systems. It calls for innovative approaches to creating new, highly productive habitats specifically designed for interested species. Agriculture has a history of increasing productivity per unit of land area so that a growing human population can be fed without large expansions of acreage. Attention should now be directed towards increasing wildlife production per unit of habitat area. Such an approach can benefit both wildlife and agriculture in the Imperial and western San Joaquin Valleys of California where wildlife considerations are impacting the management of soil salinity.

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