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Agriculture, Irrigation and Drainage on the West Side of the San Joaquin Valley, California: Unified Perspective on Hydrogeology, Geochemistry and Management

T.N. Narasimhan and N.W.T. Quinn

March 1996

MASTER

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**Agriculture, Irrigation and Drainage on the West Side of the
San Joaquin Valley, California: Unified Perspective on
Hydrogeology, Geochemistry and Management**

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SUMMARY

Recognizing the common good arising from irrigated agriculture, the Irrigation District Law was passed in 1887, implementing the principle of public expenditure on irrigation projects in the western United States. For over a century since, irrigated agriculture on the west side of the San Joaquin Valley has combined technology and innovation to contribute significantly to the economy of the State of California. At present, irrigated agriculture is practiced over an area of about 1 million hectares (2.3 million acres) on the west side of the San Joaquin Valley. Cotton, fruits and vegetables, nuts and alfalfa from this region contribute significantly to California's agricultural annual revenues estimated at 18 billion dollars. By being a major provider of food for the nation and by providing an infrastructure of jobs, agriculture on the west side plays a vital role in the social fabric of the State. Until the 1980s, the public good stemming from these agricultural activities was rarely challenged.

Part of the economic success of the west side's agriculture is attributable to the availability of large supplies of irrigation water, particularly from the Central Valley Project, administered by the U.S. Bureau of Reclamation. Although blessed with abundant resources of groundwater down to depths of 600 meters (2,000 feet) or more, experience between the 1920's and the 1950's showed that heavy pumping of groundwater leads to unacceptable land subsidence (as much as 8 meters at places) and increased cost of pumping due to declines in water tables (unconfined aquifers) and in piezometric head (semi-confined and confined aquifers). More recent information indicates that long-term pumping can lead to a decline in water quality and a decline in the suitability of water for irrigation. Thus, irrigation on the west side largely depends on imported surface waters from the Sacramento-San Joaquin Delta, with groundwater providing a secondary source, especially during years of drought.

Because of the particular geological attributes of the Coast Ranges to the west and the climatic conditions, groundwater on the west side tends to be relatively rich in dissolved salts (as compared to the areas east of the San Joaquin River), especially at the distal ends of the alluvial fans, in the inter-fan areas and in the Basin trough. Furthermore, the Basin trough historically constitute regional areas of discharge, where groundwater is forced upward toward the land surface. As a consequence, the water table tends to lie close to the land surface in these areas and the upward moving groundwater tends to deposit salts in the shallow subsurface due to evaporative concentration. The shallow water table and the propensity for salt concentration have combined to give rise to a special requirement of irrigation on the west side, namely, agricultural drainage. The need for agricultural drainage was foreseen by Hilgard over a century ago.

Over the past decades a great deal of research has focused on assessing and managing root zone moisture content and salinity for maximum crop yield. Especially with the drive towards improving irrigation water use efficiency, where water applications are more closely matched with water requirement, it is imperative that sufficient water be provided to leach accumulated salts from the root zone in order to sustain agricultural productivity. Despite the fact that the imported irrigation water is relatively fresh (300 to 600 ppm of total dissolved solids), the sheer volume of the imported water is so large that the west side imports salts to the extent of about a million tons per year.

Long-term sustainability of irrigated agriculture is clearly constrained by the salinization of soils and water, as was foreseen by Hilgard over a century ago. Even as agricultural engineers

and planners were exploring ways and means of finding long-term solutions to the salinization problem, the 1980's witnessed an unexpected development which has had a profound impact on the long-term sustainability of irrigated agriculture on the west side. The San Luis Drain, which became functional in the early 1980's conveyed drainage effluent from a 2,150-hectare (5,300-acre) area from the Westlands Water District to Kesterson Reservoir. Within a few years of receiving drainage effluent from this area, wildfowl that utilized the Reservoir for nesting and over-wintering were found to be adversely affected by selenium toxicity. The resulting public outcry over the environmental contamination at Kesterson Reservoir catalyzed a movement which became interested in assessing the negative impacts associated with irrigated agriculture and to question the sustainability of irrigated agriculture on the west side of the San Joaquin Valley. Studies were initiated to investigate the resource requirements and irreversible impacts of irrigated agriculture, and to assess the direct and indirect costs of sustaining agriculture to the taxpayer. Other questions were asked of scientists and policy makers. Should future contractual obligations for water deliveries be modified to divert water from agriculture to expand wetlands and enhance fish and wildlife? How should the intrinsic worth of benefits derived from agriculture be measured in relation to water needs of developing urban centers? These questions go directly to the heart of the 1928 amendment to California's constitution which asserted that water in California shall be used for reasonable and beneficial purposes.

Historically, California has successfully depended on science and technology to make major strides in agricultural development. At present, we are witnessing a paradigm shift; from a perception of unquestioned public good, agriculture (despite its economic strength) is now being perceived as a beneficial enterprise which is subject to the same constraints of environmental and ecological degradation as competing urban communities. This changing paradigm poses new challenges to science.

In the emerging context, science must accomplish two major tasks. The first is the short-term objective of increasing the productivity of agriculture through a greater efficiency of use of water and land. The second, longer term objective, is to continually evaluate the impact of irrigated agriculture on the environment and the diverse ecosystems that comprise the environment within the San Joaquin Valley. These objectives are complementary and of equal importance. The challenge is to bring the results of science, on the one hand, to the farmer so as to improve agricultural efficiency and on the other, to society at large so that the relative benefits of agricultural economy can be wisely weighed against the preservation of the environment and ecosystems. These short-term and long-term objectives set the stage for future research directions relating to agriculture on the west side.

Most of the research efforts in the past that have been motivated by a desire to enhance agricultural productivity have concentrated on issues relevant at the farm level. In addition to the agronomic requirements of the crops themselves, the focus of attention has been the soil zone extending from the land surface to the water table, over a depth of a few meters. From a physico-chemical point of view, past research activities at the farm level have striven to maintain moisture and salinity in the crop root zone within tolerable limits throughout the growing season. This has been achieved both through carefully timed application of water (irrigation scheduling) to flush excess salts into the groundwater and through manipulation of the water table so that the root can extract the portion of evapotranspiration needs from the water table. In turn, water table control is achieved through installation of in-line weirs and pumps, and through careful

management of drainage discharge. A current trend in research is to dynamically evaluate plant ET needs through periodic measurements of temperature, soil moisture, soil salinity and related measurements in the field. At present, the estimation of crop ET needs as well as the efficient application of water over areas that can range from several hectares to several tens of hectares on a farm scale, is limited by the ubiquitous variation of soil properties (texture, moisture content, salinity) over distances of less than a meter. Given these constraints, attempts are being initiated to create computer-aided tools which would help an individual farmer to monitor field conditions and use the information to manage irrigation on a day to day basis. The challenge for soil scientists, agronomists, irrigation engineers and hydrologists is to solve the relevant problems of significant scientific complexity and to bring the results within the reach of practical use by the farmer.

Until the advent of Kesterson and the drainage-related problems that it created, drainage management was perceived as an issue of removing excess water and salts from the crop root zone and transporting the unwanted drainage effluent to the nearest drain (the San Luis Drain) or the San Joaquin River. A careful study of the behavior of drains has shown that the root zone, the shallow water table and the drains are dynamically connected with the regional groundwater system. Because subsurface drains possess a finite radius of influence, some root zone water will escape the influence of drains and find its way to the shallow groundwater. There is evidence that the original shallow groundwater system may have been contaminated down to as much as 50 meters (150 feet) by irrigation applications. There is also evidence that the drain systems may actually draw some saline or selenium laden waters from the groundwater system below rather than from the root zone above. These experiences have recently motivated irrigation engineers to extend their interests beyond the root zone and the drain and to understand the interactions between the drains and the local groundwater system.

On a time scale of decades to centuries, the movement of groundwater and its evolving chemical quality are governed by gravity-driven forces emanating from the Coast Ranges to the west, which constitute the groundwater recharge area for the west side. On the lower parts of the valley, the hydrological and geochemical processes are subjected to small gradients (and hence, small rates of change) and occur over long periods of time. Superimposed on these are the strong perturbations imposed by irrigated agriculture involving massive quantities of imported water. Thus, at the farm level, we are confronted with the interactions between powerful and gradual regional forces and intense local forces. Geologists and hydrogeologists have traditionally concerned themselves with the regional driving forces occurring over geological time. Irrigation engineers, on the other hand, have dealt with the effects of water application and drainage on a local scale.

The environmental lobby within California has drawn attention to the fact that irrigated agriculture should be conducted without contaminating surface streams or groundwater aquifers in unacceptable ways. Driven by slow regional forces, these aquifers respond quite slowly to non-point source agricultural contamination. Therefore, for evaluating the sustainability of natural resources on the west side, it is imperative that hydrogeologists and irrigation engineers must come together to fill in gaps in knowledge and to assess the response of the soil, land and water on a time scale of decades to centuries to continued irrigated agriculture. Although the need for the long-term perspective and interdisciplinary bridges are recognized in principle, much progress remains to be made in these directions.

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"The waters which are from the heaven, and those which flow after being dug, and those which spring up by themselves, the bright, pure waters which lead to the sea, may those divine waters protect me"

The Rig Veda, VII, 49.2, Max Mueller, 1891

INTRODUCTION

Since its inception, the Salinity and Drainage Task Force (SDTF) of the University of California has supported research on a variety of topics addressing irrigation-induced water quality and environmental problems while considering the economic viability of agriculture in the San Joaquin Valley. These topics have included issues such as, soil fertility and crop productivity; water and salinity management; uptake of trace elements by plants; drainage design and management; impact of irrigation on the local groundwater system; economics of crop, irrigation and salinity management; and spatial variability of soil hydraulic properties. These research efforts have been coordinated with complementary research work by other agencies such as the United States Geological Survey, the United States Department of Agriculture's Water Management Research Laboratory and United States Salinity Laboratory, the United States Fish and Wildlife Service, the United States Bureau of Reclamation (USBR), the California Department of Water Resources (DWR) and the California Department of Fish and Game (F&G). While knowledge and databases accumulate as a result of these efforts, it is becoming clear that the various physical-, chemical- and biological effects of natural causes (hydrology, geology, geochemistry, pedology) and anthropogenic causes (irrigation, agriculture, drainage) are inexorably linked in complex ways. The consequence is that sustained use and enjoyment of vital natural resources (namely, land, water, fish and wildlife) can be achieved only by recognizing these linkages and suitably modifying human activities to achieve a balance between

competing needs for these resources.

PURPOSE AND SCOPE

The purpose of this report is to provide a broad understanding of water-related issues of agriculture and drainage on the west side of the San Joaquin Valley. To this end, an attempt is made to review available literature on land and water resources of the San Joaquin Valley and to generate a process-oriented framework within which the various physical-, chemical-, biological- and economic components of the system and their interactions are placed in mutual perspective.

Because of the breadth of the topics involved, the scope of this report is modest. It primarily focuses attention on physico-chemical processes accompanying the movement of water through soils and deeper geological formations and attempts to understand the impacts of these processes on the larger system. Consideration of plant-soil relations is restricted to the physics of the processes involved and ignores microbial and biochemical effects and interactions. We also restrict attention to the west side of the San Joaquin River, hereinafter referred to as the west side for brevity, since it is the west side that contains the highest concentrations of salts and trace elements in soils and groundwater.

A consequence of the broad vision attempted in this report is that topics and issues from a variety of disciplines are discussed. In order to provide a measure of self sufficiency of concepts needed to understand the diverse ideas, we include brief discussion of basic concepts wherever appropriate. Although an attempt has been to consult as much of the relevant published material as possible, the literature cited in this report is by no means complete.

In support of the approach ventured in the present work, two quotes are appropriate. Vaux and Tanji (1991), in analyzing future research needs for salinity and drainage, state, "Future research on salinity and drainage must focus on achieving a balance between agricultural productivity and environmental quality." Secondly, the advisory committee of the National Research Council (1989), offering guidelines to those involved with agriculture and irrigation on the west-side on research directions, states, "These factors (economic, social, legal, political and other institutional factors) cannot be considered in isolation because institutional and scientific considerations often are entwined, and effective programs to solve such problems require an

understanding of the complex interactions that occur between social and physical components."

BACKGROUND

IRRIGATED AGRICULTURE ON THE WEST SIDE OF THE SAN JOAQUIN VALLEY

Irrigated agriculture on the west side dates back to the middle nineteenth century. Irrigation-induced salinization of land had already been observed and documented by Hilgard (1889), who drew attention to the long-term consequences of irrigated agriculture. Aggressive agriculture has continued ever since, contributing significantly to the economic well-being of the State of California. Over the past century, patterns of agriculture and irrigation have continually evolved in California, responding to changing resource conditions and technological advances. This evolution has indeed been characterized by science and engineering being successfully called upon to find practical solutions to problems of agricultural productivity and profitability.

California's agricultural success owes much to the Irrigation District Law of 1887 (also known as the Wright Act), which was passed with the recognition that irrigated agriculture was beneficial to society and therefore deserving of public support. Following this, the Reclamation Act of 1902, a milestone in California's history, introduced the availability of subsidized water for irrigation. This enactment defined, for the succeeding decades, the basic objective of resource utilization, namely, agricultural productivity and profitability. The creation of the Central Valley Project in the 1930's on the basis of the Reclamation Act has had a profound influence on the economic, social and political fabric of the San Joaquin Valley ever since. However, over the past two decades, this objective has come into conflict with emerging public awareness about the environment in general and the environmental impacts of irrigated agriculture in particular. With or without further water development, greater conflict over water can be expected to occur, especially in years of shortage. No longer can demands for water be accommodated simply by the construction of a new reservoir or storage facility.

Another milestone in the history of the west side was the birth of the technology of the deep-well turbine pump during the 1920s. These pumps helped draw high-quality water for irrigation from deep aquifers, lying at depths of 600 meters (2,000 feet) or more. By the 1930's, the negative effect of this large-scale pumping began to manifest itself in the form of land subsidence over the more vigorously pumped regions of the San Joaquin Valley. Water was being mined

from soft sediments such as clays and silts at rates far exceeding their groundwater recharge. At some locations on the west side, land had subsided by as much as 8 meters (about 25 feet) by the middle 1970s. Moreover, the declines in pumping water levels ensuing from excessive pumping added significantly to the cost of lifting water. A desire to arrest land subsidence and a consideration for reducing pumping costs led to the importation of surface water supplies from the Delta to the north through the Federal pumping plant of the Central Valley Project (CVP) located at Tracy. Water deliveries from the Delta-Mendota Canal (of the CVP), which began in 1951, helped arrest subsidence and contributed to the gradual recovery of piezometric heads in the aquifers towards pre-pumping levels. Although the heads in the confined aquifers have recovered significantly, only about 10 per cent of the total subsidence recovered because of the plastic deformation properties of the sediments. The remaining 90 percent constitutes groundwater storage that has irreversibly been lost.

The depositional nature of the sediments on the west side has been such that the alluvial soils, especially those in the Valley trough at the medial and distal ends of the alluvial fans, are prone to salinity due to water-logging and rising water tables. For decades, the chief problem confronting crop yield in the San Joaquin Valley was increasing salinity due to the accumulation of soluble salts in the root zone and increasing toxicity due to trace elements such as boron. As salts build up in the root zone, the plants must expend extra energy to overcome osmotic forces and extract fresh water and nutrients from the soil. Thus, high root-zone salinity was correlated with high water-stress to the plants. To reduce this stress, the perceived solution was to flush the root zone of excess salts, to be normally accomplished by leaching with irrigation water, applied in excess of the crop's water requirement. In addition, networks of subsurface tile drains were installed to remove these flushed salts and to control the proximity of the water table to crop roots. Maintenance of a water table 2 meters or more below the ground surface was found to reduce evaporative concentration of salts in the root zone, which typically increases as water tables rise above an extinction depth of approximately 2.5 meters. This extinction depth, defined as the limit of evaporative concentration of salts, depends on soil texture and capillarity.

In order to mitigate potential salinity problems, Federal and State governments began, as early as 1957 (or perhaps even as early as 1930), drawing plans for a master drain to collect and transport subsurface agricultural drainage from the west side to Suisun Bay in the Delta. But,

the State of California withdrew support for the project in 1968 and the U.S. Bureau of Reclamation proceeded with the first stage of construction of the San Luis Drain. The first stage, about 135 km long, was completed in 1971, originating on the eastern boundary of the Westlands Water District and terminating adjacent to a series of shallow, excavated flow regulating ponds that were subsequently named Kesterson Reservoir. Only 520 hectares (1280 acres) of the 2,400 hectares (5,900 acres) of land acquired by the Federal Government for the regulating reservoirs received agricultural drainage water. In 1976, with the passage of the amended National Wildlife Refuge System Administration Act, all wetlands managed by the Fish and Wildlife Service were incorporated into a national wetlands system. Kesterson Reservoir and the adjacent 1,870 hectares (4,620 acres) were subsequently incorporated into the Kesterson National Wildlife Refuge. Between 1972 and 1978 Kesterson Reservoir received fresh water inflows. Due to financial as well as regulatory reasons, construction of the second-phase, the lower reach of the San Luis Drain from the Kesterson Reservoir to Suisun Bay was abandoned in 1979. Discharge of agricultural drain water from about 2,150 hectares (5,300 acres) of the Westlands Water District commenced in 1979 and by 1981, inflows into the Kesterson Reservoir consisted exclusively of agricultural subsurface- and surface drainage water. By 1982 all inflow to Kesterson was from subsurface drains.

The discovery in 1983 of reproductive failure of waterfowl and deformities in waterfowl embryos at Kesterson Reservoir, both attributed to selenium poisoning, received significant media attention (National Research Council, 1989). Although the media portrayed the selenium contamination at Kesterson as an environmental disaster and were instrumental in leading a significant shift in public perception of the environmental impacts of agriculture, history may be kinder to the legacy of Kesterson. Had the Fish and Wildlife Service not been involved in the operation of Kesterson Reservoir and had it not been incorporated into the National Refuge system, it is possible that early detection of selenium toxicosis would not have been made. The long term chronic consequences of selenium contamination would likely have led to many more instances of nesting failure and wildfowl mortality. The chronology of events that followed would probably have been different as well as the impacts on west side irrigated agriculture.

It is necessary to recognize here that the Kesterson experience merely helped, albeit dramatically, to focus attention on the potential environmental consequences of intensive

irrigation and subsurface drainage in an arid environment. Since the Kesterson crisis, other sites throughout the western U.S. have been identified where concentrations of selenium and other trace elements such as arsenic occur at potentially toxic levels (National Research Council, 1989).

At the present time agriculture on the west side is a dynamic enterprise. It is a major producer in the nation of fruits, vegetables, nuts, cotton and alfalfa, contributing significantly to a state-wide 18 billion dollars a year industry. None the less, the greening of California, competitiveness in a global agricultural market of the future and competition for water from growing urban communities (Farrell, 1994) combine together to pose unprecedented challenges to agriculture on the west side. Short-term concerns of productivity and profitability are compounded by deeper questions of long-term sustainability of agriculture and the environment.

THE WEST SIDE SETTING

The San Joaquin River basin extends roughly NNW-SSE, descending from the foot of the Tehachepi Mountains, northwards to its confluence of the Sacramento River in the Sacramento-San Joaquin Delta. The Valley is about 400 km (250 miles) long and about 80 km (50 miles) wide (Figure 1), bounded on the east by the Sierra Nevada Mountains and on the west by the California Coast Ranges.

Physiographically, there are two hydrologic basins in the San Joaquin Valley. The San Joaquin Basin extends south of the Sacramento - San Joaquin Delta and is drained by the San Joaquin River. The Tulare Basin extends from the foot of the Tehachepi Mountains northwards to a gentle topographic rise along a line a little to the north of the Los Gatos Creek and the Kings River and has no drainage outlet. The Tulare Basin receives water from the rivers to the north only during years of extreme flooding. A fresh water lake, the Tulare Lake, occupied this depression at the turn of the century (Preston, 1979) and has since been converted to agricultural lands. The Kings River, the Kaweah River and the Tule River drain into the Tulare Lake. Further south, the Kern River empties into the smaller Buena Vista Lake. Lake Isabella is a reservoir on the Kern River, upstream of Bakersfield. The Pine Flat Reservoir is located on the Kings River. Fresno Slough connects the Tulare Basin with the San Joaquin River, across the topographic rise. Depending on severity of flooding, water may flow either way on this channel.

The major tributaries to the San Joaquin River that drain the east side of the San Joaquin

Basin are the Fresno, Merced, Tuolumne and Stanislaus Rivers (Figure 2). The headwaters of these rivers contain water of high quality that are important in providing dilution to the San Joaquin River that receives drainage of poor quality from west side sources. Many surface water impoundments have been created behind Dams on the tributaries of the San Joaquin River for flood control and irrigation water supply. As shown in Figure 2, these include Millerton Lake (on the San Joaquin River), Lake Hensley (on the Fresno River), Lake McClure (on the Merced River), New Don Pedro Reservoir (on the Tuolumne River) and the New Melones Reservoir (on the Stanislaus River). On the west side of the San Joaquin Basin, the major facility is the San Luis Reservoir which is hydraulically connected to the California Aqueduct and Delta Mendota Canal and which provides off-stream storage for both the Central Valley Project and State Water Project.

Prior to the construction of the CVP and the Delta Mendota Canal, San Joaquin River water was used directly to irrigate land on the west side of the San Joaquin Valley. However, with the construction of the CVP, water released from Friant Dam was diverted to the Tulare Basin through the Friant-Kern Canal and water from the Delta Mendota Canal was made available to these "exchange contractors" for irrigating these lands formerly served by the San Joaquin River. The Mendota Pool is a CVP storage reservoir, located at the terminus of the Delta Mendota Canal, which provides water to a number of supply canals which take the water north to irrigation turnouts located along their length.

Historically, agriculture on the east side of the San Joaquin River has largely been in small holdings of less than 40 hectares (100 acres), whereas on the western side much land is owned by major corporations and holdings are much larger. The total irrigated area on the west side is about 1 million hectares (2.3 million acres; Tanji, 1990), of which, 0.36 million hectares (0.89 million acres) are affected by salinity and sodicity, 0.25 million hectares (0.61 million acres) by high water table and 0.38 million hectares (0.93 million acres) by poor groundwater quality. Cotton is the major crop grown (over 49% of the irrigated area) on the west side, with lesser areas planted with tomatoes and melons. Commodity prices and expected crop revenues have a significant impact on cropping practices on the west side. Currently, it appears, a trend is

Figure 1: Map of the San Joaquin Valley within the Great Valley of California. The dotted line delineates the valley basin. Stippled areas denote the Sierra Nevada Mountain Range (From Erskine et al. 1992)

developing towards growing more fruits, nuts and vegetables in preference to cotton.

Subsurface tile drains have been installed in nearly 55,000 hectares (135,000 acres) of irrigated lands (Salinity and Drainage Task Force, 1992) to control seasonally high water tables and to dispose of salts flushed out from the root zone. To manage the application of irrigation water to cropland, a variety of irrigation methods are employed. Pre-plant irrigation and irrigation scheduling during the growing season are commonly practiced to improve irrigation water-use efficiency and maximize crop yields. Crop rotations are practiced on some lands to sustain soil fertility and control crop pests.

Administratively, the west side is divided into water- and drainage districts (Figure 3). The largest water district on the west side is the Westlands Water District, most of which lies in the Tulare Basin. Westlands Water District has no natural drainage outlet and does not have a historic right to convey drainage water to the San Joaquin River. The San Luis Drain, with its terminus at Kesterson Reservoir, provided drainage relief to only 2,150 hectares (5,300 acres) of irrigated land within a 17,000 hectare (42,000 acre) area in the north-east corner of Westlands Water District until 1986. Because of selenium toxicity, discharge of subsurface drain water from these 2,150 hectares (5,300 acres) of the Water District ceased in 1986. As a result, farmers have been forced to find local solutions to the problem of drainage management and salt disposal within the District.

Although the on-farm tile drains in Westlands that discharged through collector drains into the San Luis Drain were plugged in early 1986, on-farm drains in water districts north of Westlands in the Grasslands Basin that deliver salt- and selenium-contaminated water to the San Joaquin River continue to operate. These drains convey between 55.5 million cubic meters (45,000 acre-feet) and 92.5 million cubic meters (75,000 acre-feet) of combined surface and subsurface drainage water to the river annually, depending on annual precipitation and project water deliveries to agricultural contractors (San Joaquin Valley Drainage Program, 1990). It is relevant to note that there is another important aspect to the disposal of drain effluents into the San Joaquin River during times of peak flow. Although it is true that such a practice satisfies the regulatory constraints of the State Water Quality Control Board, these effluents contribute to the gradual increase of Se in the San Francisco Bay. Therefore, it is necessary to evaluate the long-term changes in the Se content in the Bay and their relation to the disposal of drain waters

Figure 2: Major reservoirs of the San Joaquin River Basin: (1) Lake Isabelle, (2) Pine Flats Reservoir, (3) Millerton Lake, (4) Lake Hensley, (5) Lake McLure, (6) New Don Pedro Reservoir, (7) New Melones Reservoir, (8) San Luis Reservoir (Modified from Lay Person's Guide to California's Rivers, Water Education Foundation, Sacramento, California, 1992)

into the San Joaquin River.

Orlob (1991) analyzed historic data to understand the state of balance between salt import and salt export into and from the San Joaquin Basin. Since the completion of the CVP's Delta-Mendota Canal, over 18 million metric tons of salt have been imported into the Valley through water deliveries. Water quality in the Delta-Mendota Canal tends to be inferior to water quality in the California Aqueduct owing to the proximity of the Tracy pumping plant to the San Joaquin River. Typical salinity of the Delta-Mendota Canal is in the range of 400 - 500 mg/l total dissolved solids. Orlob (1991) has estimated an average salt accretion to the San Joaquin Basin through the Delta Mendota Canal of between 1,100,000 and 1,420,000 metric tonnes per year.

Since the construction of the surface water reservoirs on the east side of the San Joaquin Valley and subsequent diversion of water along the Friant-Kern Canal, the average annual flow in the San Joaquin River (as measured at the Vernalis gaging station) has declined by about 16 billion cubic meters (13 million acre feet). Consequently outflow of salt from the San Joaquin Valley is now much smaller than that imported into the San Joaquin Valley by way of the Delta-Mendota Canal and the California Aqueduct. The remaining salt accumulates in the soil or in the groundwater aquifers beneath agricultural land on the west side. At the present rate, according to Orlob (1991), the net import of salt annually would be about 2.2 metric million tons by the year 2007.

To address the salinization, drainage and drainage related problems on the west side of the San Joaquin Valley, the following measures have been investigated and, in many cases, implemented. The pressure to implement these measures has never been greater in California's history.

- Reduction of "deep percolation"¹ losses to the water table through the adoption of water conserving irrigation technologies and practices, better irrigation scheduling and changes in cropping practices .
- Reuse of drain water, through the use of salt-tolerant crops and agro-forestry.

¹ The phrase "deep percolation" is used here to denote the downward movement of water below the root zone, past drains to the local groundwater system.

Figure 3: Administrative districts of part of the western San Joaquin Valley

- Manipulation of the water table to meet part of the crop evapotranspiration requirements.
- Conjunctive use of groundwater to meet a portion of crop needs.
- Improved instrumentation and monitoring systems to produce accurate and timely information and improve access of this information to growers.
- Development and installation of monitoring systems to progressively evaluate changes in soil and water quality in the terrestrial and aquatic ecosystems over time.

Agriculture is no longer viewed by the public as completely a benign enterprise. This has partly decreased the power of the agricultural lobby and has most recently led to the unprecedented re-evaluation of Federal water contracts within the CVP, resulting in the so-called "Miller Bill" (CVP IMP ACT PL 102-575 Title 34). The Environmental Impact Statement (EIS) requirement for contract renewal for each CVP contract may end up reducing the total allocation of federal-developed water to agriculture. The Miller Bill mandates that 986 million cubic meters (800,000 acre-feet) of water, currently allocated to agriculture, be redesignated for fish and wildlife purposes. During the middle of the 19th century California boasted in excess of 1.6 million hectares (4 million acres) of wetlands (National Research Council, 1989), presumably including estuarine wetlands such as the Suisun marsh. As a consequence of the activities stemming from the Reclamation Act of 1902 and land development for agriculture, municipalities and industry, the wetland area decreased dramatically to less than 400,000 hectares (a little over a million acres) by the early 1920s (Figure 4) and by 1977 wetlands acreage in California had dwindled to about 10% of what it was in 1850. The Miller Bill ostensibly seeks to redress the loss of wetland acreage that has occurred over the past century.

At the threshold of the 21st century, agriculture on the west side of the San Joaquin Valley finds itself constrained by the seemingly opposing objectives of economics on the one hand and the less tangible objectives of quality of life, stemming from prosperity. The vision of science and technology is that through a judicious management of water and land resources, California can continue to benefit from agriculture over many decades to come. This vision, nevertheless, has to be tempered by the recognition that the final decisions of management will need to weigh scientific solutions against social questions. In this context, it seems

Figure 4: Wetland losses in California, 1850-1977 (National Research Council, 1989)

reasonable to assume that a sound grasp of the scientific and technological consequences of management alternatives is a prerequisite to help choose between competing social decisions. Consequently, science and technology have to appreciate their objectives in a broader context and provide information in a fashion that is amenable to social decision-making. Motivated by this perceived connection between science and technology on the one hand and social decisions on the other, we now pass on to assess our current knowledge of issues related to agriculture, drainage and water management on the west side of the San Joaquin Valley.

CURRENT STATUS OF KNOWLEDGE

THE LARGE SCALE

A Unifying Framework

Scientific research needed to support agricultural activities on the west side is concerned with problems associated with individual fields on a single farm to multiple adjacent fields constituting the farm itself, to water- and drainage districts that include a number of farms, to the entire west side of the valley. On the temporal scale they include problems of infiltration response and evaporation effects on a time-scale of hours; through irrigation scheduling during the growing season and crop rotations spanning a number of years; to long-term water-delivery contracts and land retirement decisions over several tens of years. Thus, research concerns of the west side span a variety of scales in space and in time. On-farm decisions will, of necessity, depend on process-intensive small spatial scale questions, giving consideration to site-specific attributes. They will also be concerned with small and intermediate time scale issues, not exceeding a few years. On the next larger scale, water districts and managers are concerned with questions pertaining to subdistricts covering thousands to tens of thousands of acres of land, with time scales larger than a single season. Although answers to these questions will be influenced by the variety of site-specific and intra-seasonal attributes of the farm scale, such variations will have to be aggregated and integrated into fewer parameters and objective functions, perhaps less process-intensive. At the largest scale are issues pertaining to a district and to issues pertaining to interdistrict linkages. The relevant time scale may vary from a season (e.g. managing water quality in the San Joaquin River) to several decades (contractual obligations, response to global climate change). Each of these scales has its own importance in the overall endeavor and the

attributes of these scales are interlinked dynamically in both directions. For the overall venture to be successful, information must flow freely in both directions between the scales. Therefore it is a basic necessity to formulate a unified framework within which issues and attributes on all spatial and temporal scales are interlinked.

Water, which starts as precipitation and moves on the land surface as surface runoff or infiltrates to recharge aquifers has the ability to dissolve and transport sediments, minerals and nutrients. It constitutes the universal link which binds together issues of irrigated agriculture and the environment on all spatial and temporal scales on the west side. Therefore we shall use water as the unifying theme for total system integration and use it as the basis to formulate the needed overall framework for system integration.

Early in the 1960s an important development in the field of hydrogeology was the formalization of ideas concerning the dynamic behavior of water in groundwater basins; the notion of Regional Groundwater Motion (Toth, 1963). The simple but yet profound basis of this conceptualization is that water, precipitating as rain or snow at higher topographic locations, moves more or less vertically downward into recharge areas (Figure 5). Then, driven by gravity and its own potential energy, it begins its travel towards a point of discharge, the ultimate discharge point being the ocean. Below the water table in the recharge area, the flow path shifts to a subhorizontal aspect and groundwater travels laterally, subject to the nature of the geological formations, before encountering discharge areas. Below discharge areas the flow paths become vertically upward. Between an area of recharge and one of discharge, the path length may be as short as a few hundreds of meters in a shallow ground water system or as long as tens of kilometers in deep systems. On a vertical cross section of a geologic system, shallow, intermediate, and deep ground water subsystems will coexist, being separated by regions of stagnation. Careful study of the groundwater system on the west side of the San Joaquin Valley by previous workers (Belitz, 1988, 1990; Davis and Coplen, 1989) confirms the relevance of this conceptual model and its utility in understanding the role the groundwater system has played in both the evolution and current state of irrigation and drainage on the west side. Concomitant with the recognition of three dimensional, gravity driven flow patterns in groundwater systems, it was also recognized by geochemists (Chebotarev, 1955) that the geochemistry of groundwater is intimately influenced by the recharge-discharge relationships. Thus, in a broad way, waters

from recharge areas tend to be oxidizing and richer in calcium and bicarbonate. On the other hand discharge areas tend to be characterized by reducing conditions and enriched in sodium chloride.

For these reasons, it is rational to begin the study of the west side agriculture with a discussion of its regional geological and hydrogeological setting.

Regional Geology

Belitz (1988, 1990) provides an account of the state of the groundwater system as it existed at the turn of the century and how its character has changed to the present time due to intensively irrigated agriculture. Although his account addresses the central part of the west side, largely falling within the drainage areas of the Panoche Creek and Little Panoche Creek, the ideas presented can be applied reasonably well to the entire west side of the Valley.

Because the regional groundwater system is driven by gravity, physiography and geomorphology play a decisive role in determining its character. The west side is characterized by a fairly simple topographic pattern; an easterly sloping flank of the Coast Ranges extending for over 125 kilometers (80 miles) in the NNW-SSE direction (Figure 6). The distance from the boundary of the Valley deposits to the San Joaquin River varies slightly around 32 kilometers (20 miles). Over this distance, the elevation declines from about 182 meters (600 feet) to about 49 meters (160 feet) above sea level. The upper slope (comprising alluvial fans), from 182 meters (600 feet) to about 91 meters (300 feet), tends to be steeper than the lower slopes. Four intermittent streams, from south to north, the Los Gatos Creek, the Cantua Creek, the Panoche Creek and the Little Panoche Creek have created important geomorphic features of the Valley by virtue of their well-developed alluvial fans (Figure 7).

Sediments of recent alluvium deposited by the action of the aforesaid streams cover much of the west side, from the flanks of the Coast Ranges to the vicinity of the river. On the upper slopes and in the prominent alluvial fans, the sediments tend to be coarse-grained, having been deposited by episodic, high-energy stream flows. In the inter-fan areas and in the lower slopes of the Valley, the sediments show a flood-plain depositional character and consist of fine-grained materials. Mass-wasting, mud flows and surge flows associated with the high energy sediment transport by ephemeral and intermittent streams appear to play an important role in controlling

Figure 5: Schematic diagram of a regional groundwater system showing local-, intermediate and regional flow systems (After Toth, 1963)

NATIONAL GEODETIC VERTICAL DATUM OF 1929
CONTOUR INTERVAL 40 FEET

0 10 20 MILES
0 10 20 KILOMETERS

Figure 7: Alluvial fans and intermittent streams of western San Joaquin Valley (after Deverel and Gallantine, 1988). Stippled areas denote alluvial fan deposits

the physical- as well as the chemical properties of the sediments.

Marine sediments, ranging in age from Jurassic to Miocene age are exposed along the ridge crest of the Coast Ranges (Presser et al., 1991). Two members of this sequence, the Moreno Formation (upper cretaceous to paleocene) and the Kreyenhagen Formation (eocene to oligocene) are exposed over a 32-kilometer (20-mile) stretch of the Moreno Ridge. Despite their limited extent, these formations play an important geochemical role because of their high selenium content. Following the miocene, during pliocene and pleistocene periods the marine conditions gave way to continental and lacustrine conditions. The Tulare formation of pliocene to pleistocene age underlies the alluvium over much of the west side.

The Corcoran Clay of the Tulare formation, approximately 30 meters (100 feet) thick, constitutes an extensive marker horizon beneath the west side. The alluvial sediments overlying the Corcoran Clay decrease in thickness from a maximum of about 244 meters (800 feet) on the Valley margins to less than 30 meters (100 feet) in the vicinity of the San Joaquin River (Figure 8). In the Valley trough, the coast range alluvium, characterized generally by fine-grained sediments, gives way to the alluvial Sierran sands derived from the Sierra Nevada mountains. The coarser Sierran sands contain water with chemical characteristics distinct from the sediments of the Coast Ranges alluvium. The alluvial sediments overlying the Corcoran Clay are frequently referred to as the "semi-confined" zone.

Regional Groundwater Flow

As one might expect, the Coast Ranges constitute the groundwater recharge area for the west side. At the turn of the century, before intense pumping commenced in the 1920s, the piezometric heads in the deep aquifers underlying the Valley floor were reportedly so high that free-flowing artesian wells were common along a long, narrow zone along the river (Figure 9). The physical disposition of the artesian zone, extending parallel to the trend of the Coast Ranges, is an indication that the regional groundwater system is driven by recharge from the Coast Ranges. Based on stable isotope data of water samples from wells located above and below the Corcoran clay, Dubrovsky et al. (1990) infer that groundwater may also be leaking vertically through the Corcoran clay and recharging the deep aquifers, both due to pervasive flow through the formation and due to the several hundred wells which are screened in horizons above and

Figure 8: Idealized east - west geological cross section across the western San Joaquin Valley (From Belitz, 1988)

below the Clay.

The development of the west side of the San Joaquin Valley for irrigated agriculture and the advent of deep-well turbine pumps in the 1920s drastically changed the groundwater flow system. Groundwater became an important component of irrigation water and, responding to post-second-world-war boom in the economy, groundwater pumpage increased by a factor of four, reaching a maximum of about a million acre-feet per year between 1950 and 1970. Most of this pumpage was from the confined aquifer below the Corcoran Clay. However, pervasive land subsidence on the west side (Figure 10) and increased cost of pumping called for a reduction in groundwater pumpage and eventually led to the importation of water from the Delta and the construction of the CVP and SWP conveyance facilities.

Irrigation Wells

Gronberg et al. (1990) provide a summary of the distribution of wells on the west side. Although nearly 6,000 wells are known to exist in the Valley, useable information is available only with respect to about 2,550. Nearly two-thirds of these wells are completed in the semi-confined zone overlying the Corcoran Clay. Due to the general poor water quality within the shallow part of this zone (< 16 meters from land surface), most of the wells in the shallow, upper portion are passive, observation wells. Production wells in the semi-confined zone are typically greater than 16 meters (50 feet) in depth. The Coast Range alluvium in the semi-confined zone generally contains fine-grained sediments. Because of the larger surface area of contact between water and solids in these sediments and longer residence times, these sediments tend to contain waters of poorer quality compared, for example, with waters of the Sierran Sands to the east of the San Joaquin River. Therefore, in the Valley trough and on the margins of the alluvial fans irrigation wells are screened in the Sierran Sand aquifer which contains coarser, cleaner sands and better quality water. Because of the reducing nature of these sands selenium is retarded and appears to be converted to reduced, less mobile species. Hence selenium levels in pumpage from these sands tends to be low. Wells in the semi-confined zone have screens typically a few meters in length.

Some 533 wells are screened in both the semi-confined zone and the confined zone allowing communication between confined and semi-confined aquifers. Although the volume of flow

between the aquifers has yet to be quantified some hydrogeologists believe that they may account for some of the variability in the groundwater flux across the Corcoran Clay over the west side of the San Joaquin Valley.

Wells penetrating the confined zone below the Corcoran Clay are generally restricted to the upslope areas at the head of the alluvial fans beyond the extent of the Sierran sands. According to Gronberg et al. (1990), 410 wells tap the confined zone with open screen intervals in excess of 30 meters (100 feet). Examination of water table data and potentiometric data for 1984 by Belitz (1988,1990) showed the existence of a pronounced groundwater divide approximately midway between the Valley trough and the Coast Ranges. This divide shown in plan in Figure 11, and shown in cross-section in Figure 12, has presumably occurred due to overdraft of groundwater by pumpage to the west and by leakage from the Aqueduct. Clearly the pre-development areal distribution of recharge and discharge areas of the west side has been significantly modified by the pumpage, and has led to a very complex groundwater hydrology and distribution of contaminants within the semi-confined aquifer.

Irrigation and Shallow Groundwater System

Irrigation activities on the west side which have occurred for many decades have interacted significantly with and modified the pre-existing groundwater flow patterns, especially recharge-area and discharge-area relationships. Application of irrigation water causes water tables to rise in the shallow semi-confined aquifer, leading to an increase in the vertically downward movement of water. Because of the large areal extent of applied irrigation water on the west side, the resulting artificial recharge has significantly exceeded natural groundwater recharge by rainfall and stream flows. Williamson et. al. (1985) estimated that between 1961 and 1977 irrigation recharge was as much as 40 times that of the natural recharge.

Applied irrigation water directly affects the shallow groundwater system. In turn, the dynamics of water flow and water table fluctuations in the shallow aquifer are intimately related to local topographic variations. Very little attention has apparently been given by previous workers to understand such interactions on the basis of data from piezometer and tensiometer nests. Fio and Deverel (1991) studied, using nests of piezometers, the dynamic interactions between applied irrigation water, two tile drains, the water table and the shallow aquifer at a site

where drains had been in existence for 15 years. Their data, interpreted in conjunction with numerical simulations, suggest that the drains capture significant quantities of resident groundwater in the shallow semi-confined aquifer as well as deep percolation from the crop root zone immediately above the drain. Based on piezometer data down to a depth of 30 meters (100 feet) they inferred that the flow direction was upward at the site from about 16 meters (50 feet) below land surface downwards to about 30 meters (100 feet), below which flow is presumably downwards. That is, a horizontal groundwater divide seems to exist below 30 meters (100 feet) depth. It is not clear, however, whether the upward flow observed by them is a manifestation of the regional flow pattern. During periods of irrigation the gradient is reversed, causing the flow direction to change in the shallow zone, leading to downward migration of salts and soluble trace elements leached from the root zone. Grismer and Woodring (1987) investigated the importance of lateral flows to drains on the west side from the regional groundwater flow system and concluded that the problem has to be studied on the scale of a township (intermediate scale). They also found that the data required for credible studies on this scale were not available.

Regional Hydrogeochemistry

The regional hydrogeochemistry of the San Joaquin Valley is governed by the regional groundwater flow system and by the character of the source rocks. According to Davis and Coplen (1989), the hydrogeochemistry of the west side can be understood in terms of two distinct geochemical units. The deep aquifers below the Corcoran Clay with thickness varying from 300 meters to 730 meters contain very old waters (615,000 to 725,000 years before present). These sodium sulfate waters are thought to be mixtures of waters derived from the Sierra Nevada mountains to the west as well as the Coast Ranges. Fairly well isolated by the poorly permeable Corcoran Clay, these waters are known to have a fairly uniform composition. The aquifers above the Corcoran Clay contain waters which are distinctly different in composition from that of the deeper aquifers. Much richer in mineral content, the waters of the shallow aquifers exhibit a great deal of spatial variability in chemical composition. As we shall see below, the waters of the shallow aquifers can be divided into Coast Range waters and Sierran waters.

In the broadest sense, groundwater in the Coast Ranges alluvium differs markedly from that

Figure 9: Water Table contours and extent of the artesian zone in the western San Joaquin Valley, 1908 (From Belitz, 1990)

Figure 10: Land subsidence induced by groundwater pumpage in the western San Joaquin Valley, 1926-1972 (From Belitz, 1990)

Figure 11: Water Table contours in October 1984 showing a groundwater divide caused by groundwater pumpage (From Belitz, 1990)

Figure 12: Generalized hydrogeologic cross section across the western San Joaquin Valley in 1984, showing vertical flow patterns and groundwater divide (From Belitz, 1990)

in the Sierran sands. The former contains significant quantities of nitrate, boron and selenium while that in the latter is significantly higher in arsenic, molybdenum and manganese (Dubrovsky et al., 1990).

The special environmental concerns which arose from the selenium toxicity problem at the Kesterson Reservoir in the early 1980s provided an impetus for several researchers from the United States Geological Survey to study the regional geochemical factors governing salinity as well as the distribution of trace elements in the groundwater system. Reconnaissance studies by Presser et al. (1991) have shown that selenium, which occurs mostly in a reduced elemental state in the marine shales, has been oxidized to more soluble selenite and selenate forms. From these observations one may infer that groundwater in the recharge areas are characterized by an oxidizing environment. In the distal parts of the fans, soluble selenates may occur with sulfate and other salts in evaporite deposits. These evaporite deposits are typical of groundwater discharge areas, where salts are moved to the land surface by upward-moving groundwater and subjected to evaporative concentrations.

As groundwater moves down-gradient into the Valley trough, its oxidation potential tends to decrease. Also, Ca tends to precipitate gradually in the form of calcite (calcium carbonate) and gypsum (calcium sulfate) (Doneen, 1967). Thus, groundwater in the Valley trough, in the vicinity of the San Joaquin River tends to be richer in NaCl and Na₂SO₄ and is characterized by lower oxidation potential as compared with upstream areas. Dubrovsky et al. (1990) carefully studied the vertical variations in groundwater chemistry at a site near the Mendota airport where oxidizing irrigation waters have displaced native groundwater to depths in excess of 16 meters (50 feet) over a protracted period of time. They found that prior to irrigation, the Sierran sand aquifer was part of a regional discharge area, characterized by low oxidation potentials and enriched in dissolved iron and manganese. Prior to irrigation, selenium had been evaporatively concentrated in the near-surface soils at this site over a long period of time. Due to vigorous pumpage of the Sierran aquifers for irrigation, the water table declined dramatically between the late 1950s and the middle 1970s. This water table decline presumably led to a seasonal downward movement of groundwater and the downward transport of salts and trace elements. As the displacement proceeded, mobile selenium was removed from the aqueous phase by reduction to Se⁰, sorbed and/or precipitated in the vicinity of the interface between the two waters of

contrasting redox states. Deverel and Fujii (1987) provide evidence to show that selenium has been evaporatively concentrated with other salts in areas of regional groundwater discharge and that NaCl and Na₂SO₄ waters are being displaced by waters rich in CaCO₃ and CaSO₄. These findings suggest that surface- and groundwater transients and redox conditions play a significant role in determining soil and groundwater chemistry in the near-surface soils and groundwater aquifers.

Hydrogen isotope concentrations in groundwater have been used as a marker to estimate the depth penetration of irrigation deep percolation after the completion of the CVP facilities in the 1960's. These data have also been interpreted to estimate the regional depth distribution of salts and trace elements in the semi-confined aquifer. Gilliom (1991) has suggested that in the vicinity of the Panoche Creek alluvial fan, most salts and trace elements leached from the near-surface soils are contained in a zone between 10 meters (30 feet) and 46 meters (150 feet) below the land surface.

The chemical nature of soils in the west side is known to be significantly related to regional geologic setting and groundwater chemistry. Southard et al. (1986) studied soil samples from 8 transects extending from the Coast Ranges on the west to the San Joaquin on the east. They found that in the upper parts of the alluvial fans selenium content in the soils decreased with depth, suggestive of the important role played by sediment transport on soil chemistry. In the medial and distal parts of the fans selenium content increased with depth, presumably indicating that the element was being displaced downwards by irrigation water. The selenium variation with depth also indicated that the rate of downward displacement decreased with depth as oxidation potential decreased until reductive immobilization occurred in the vicinity of the interface with Sierran Sands of low redox potential. With regard to major chemical constituents, these authors found that sodium and chloride increased towards the river. This observation is in conformity with classical pattern of groundwater evolution in regional systems.

Doner et al. (1989) carried out a comparative study of archival soils collected in 1946 and contemporary soils on the west side with special focus on selenium and arsenic. Because of the aridity of the region, these soils were notably poor in organic matter and hence in a general state of oxidation. The soils derived from the Coast Ranges sediments were found to be richer in selenium and arsenic than those derived from the Sierran sediments in the axial trough of the

west side. It was found that selenium in its oxidized form of selenate tended to be mobilized and leached from the soil. Therefore, contemporary soils in the irrigated areas were found to contain less soluble selenium than the unirrigated soils. Arsenic in contemporary soils was found to exceed those in archival soils, suggesting presumably a pesticide source.

Doneen (1967) carried out a study of sediments collected from bore holes at 19 different locations along the then-proposed alignment of the San Luis Drain. Samples were collected from depths varying from 16 meters (50 feet) to 160 meters (500 feet). The samples from the axial trough of the valley (derived from the Sierran sediments) were found to have lower salt content than those of the fans (derived from the Coast Range sediments). Virgin soils were found to contain more salts than irrigated soils, suggestive of active leaching. Depth profiles in the medial and upper parts of the fans were found to contain significant amounts of gypsum. Similar findings were made by Fujii et al. (1988) who collectively studied soils and sediments from three locations, each with a drain system of different age (1.5 years, 6 years and 15 years).

It is reasonable to infer from available data that the relatively fine-grained nature of the Coast Ranges sediments (Laudon and Belitz, 1991) as well as their origin in the chemical weathering of marine sediments contribute to the higher salt content of the soils derived from them. This, combined with the oxidation state of the system plays an important role in the trace element of groundwater chemistry of the west side. In these soils selenium occurs sorbed on to soil particles in the form of selenite.

The dependence of selenium geochemistry on the oxidation state has further been established by studies at the Kesterson reservoir by Tokunaga et al. (1994). At Kesterson, pond-bottom sediments, rich in organic matter and submerged under water, are generally under anaerobic, reducing conditions. Experimental observations using synchrotron radiation by Tokunaga et al. (1994) have shown that under the reducing conditions selenium usually exists in the zero-valent elemental form in the soil matrix.

THE FARM SCALE

Crop-Yield, Salinity and Irrigation

Agricultural productivity and profitability are important factors influencing on-farm decisions on the west side of the San Joaquin Valley. Investments in innovative irrigation technologies,

tile drainage and management practices are predicated on the sustainability of agricultural production and the willingness of banks and other lending institutions to take calculated risks on obtaining returns to these investments. Recognizing the importance of profitability to agricultural decision makers, research undertaken by scientists, engineers and agronomists on the west side over the past several decades has focused on issues related to increasing crop production and maintaining the fertility of the soil.

Root Zone Moisture and Salinity

Clearly, a key to maintaining high crop yield is to manage the moisture content, aeration and salinity in the root zone. Except for some phreatophytes, most crops cannot tolerate waterlogging of the root zone for extended periods; rather they require unsaturated conditions in which moisture and circulating air coexist in the root zone. Given such an environment, plants extract water and selected salts from the soil for their growth and sustenance. Although much remains to be understood about the mechanisms of uptake of water and nutrients by plant roots, it is generally believed that the uptake of water and salts by the plant roots is controlled by physical- and chemical driving forces. In the unsaturated soil, water is held in the pores by capillary forces stemming from the affinity of water to bind to the surface of the soil particles. Capillary forces progressively become large with decreasing moisture content. Hence, to take water from the soil, plants have to expend energy to overcome capillary forces and gravity. Moreover, when water in the root-zone has high salinity, osmotic potentials come into play and plants also have to spend additional energy to extract fresh water. When they are forced to expend excessive energy because of high root zone salinity, plants become "stressed". When moisture content in the root zone is relatively low, water is held in small pores under high capillary pressures, requiring plants to expend large amounts of energy to obtain the water necessary to meet transpiration needs and retain turgor² pressure within the plant tissue. When turgor pressure declines below a critical level, plants wilt, the most visible early signs of plant

² Turgor pressure is the fluid pressure inside a plant cell which controls swelling and contraction of the cells.

stress. To achieve maximum crop yields, water content in the root zone should be at an optimal level over the entire crop growing season (neither too high to impair oxygen circulation nor too low to require high expenditures of energy to extract water). Salinity in the root zone must not rise above a certain, crop-specific, threshold level for an extended period of time. Certain crops such as cotton, wheat and sorghum exhibit greater tolerance to salinity than shallower rooted vegetable crops such as melons and tomatoes.

The volume of water required for crop establishment and growth is largely determined by the crop's ET requirement, the volume of water lost to the atmosphere from plant leaf transpiration and direct evaporation from the soil surface. This quantity varies from crop to crop and is also affected by factors such as stage of growth, local climate, soil salinity, water table depth and wind. Based on years of field experience (Westlands Water District, 1984) the ET requirement has been shown to vary from less than 1 acre-foot per acre for melons and peas to as much as 4.2 acre-feet per acre for alfalfa (hay).

Many field-scale, multi-year experiments have contributed to current knowledge of the ability of plants to tolerate stress and salinity. Although most plants do not like stress, some specific plants such as cotton may stand stress without adverse effects on yield during some part of the growing cycle (Ayars et al., 1990). Certain crops such as cotton presumably benefit from stress applied at critical times during the growing season which can help to stimulate seed production.

Because of the importance of moisture and salt regime in the root zone, understanding the physics of processes affecting these factors is important in the determination of crop yield. The currently used basis for such research is the Richards equation (Richards, 1931), which describes the transient movement of moisture in an unsaturated soil (that is, soil not saturated with water). The solution of this difficult-to-solve equation has been greatly facilitated in recent times with the advent of the digital computer. Many researchers now use mathematical models to study the dynamics of flow in the root zone, giving consideration, among other factors, to the dependence of hydraulic conductivity and soil-moisture-capacitance on the moisture potential as well as other factors. Among the early workers in this area of research one may mention Hanks et al. (1969) and Bresler and Hanks (1969). Using appropriate forcing functions such as rainfall, irrigation, evapotranspiration and the fluctuation of the water table, models developed by these researchers sought to quantify the variations in moisture content and water fluxes in and around

the root zone. In turn, the moisture content and water flux could be used to dynamically analyze the transport of salts and dissolved constituents as governed by advection, hydrodynamic dispersion and molecular diffusion (Freeze and Cherry, 1979).

A fundamental attribute of the Richards equation is that it is an equation of mass balance with reference to water. Two important components of the soil system which affect mass balance of water are transpiration and uptake of water by plants. Both ET and plant uptake constitute important external boundary conditions to the Richards equation. Therefore, data pertaining to these conditions have to be generated from independent experiments or models in order to analyze water balance in the root zone. Recently, methods based on micrometeorological data have been investigated by Parlange et al. (1993) and Katul et al. (1993) to estimate evaporation and soil hydraulic diffusivity on the field scale. Based on a detailed study of bare soil evaporation from salt-encrusted soils at the Kesterson Reservoir, Zawislansky et al. (1991) concluded that the evaporation rate in such a soil is usually small, being dominated by vapor transport.

For on-farm design and planning, simple empirical models of evaporation and transpiration are often used to make design and management decisions relating to crop irrigation scheduling and crop production. Here it is pertinent to mention irrigation scheduling software such as ROY; SWAP-ET (Orange Software, J.M. Lord) and the expert system AGWATER which give consideration to evaporation and transpiration in irrigation scheduling.

Because the ability of the plant root to extract water efficiently from the soil is critical to crop yield, agronomists have devoted attention to developing techniques for quantifying uptake of water by plants. The interchange of water between the plant root and the soil can be considered, as a first approximation, to be dictated by two different driving forces. The first, predominant force, which is hydromechanical in nature, drives water from the soil to the root when the hydraulic potential (or, hydraulic head) inside the root is less than that in the soil. The hydraulic head includes components due to gravity as well as matric potential (or, moisture suction). The uptake in this case is inversely proportional to the root hydraulic resistance arising from root geometry, the biomechanical properties of the root tissue and the hydraulic resistance of the soil in the vicinity of the root.

The second force arises from osmotic processes when the soil water and the cells within the

plant root differ in solute concentration. The root is known to behave as a semipermeable membrane, allowing the free flow of water but preventing the movement of relatively large dissolved ions. The nature of the osmotic drive is such that fresh water tends to move in the direction of increasing salinity across a semipermeable membrane. As the soil water salinity increases, increasing osmotic forces will tend to reduce the movement of fresh water from the soil to the root. At very high soil-water salinity this flux is reduced to near zero or even reversed which can prevent the plant from extracting adequate moisture from the soil to replace transpiration losses and lead to permanent wilting; the state of plant stress which does not allow recovery. When the soil moisture content is low and soil salinity is relatively high, the osmotic gradient between the plant and the soil solution may be significant. In this case both the hydromechanical and osmotic forces should be given consideration in estimating root uptake of water. Gardner (1960) suggested the use of a mechanistic model for plant water uptake restricting attention to the difference in hydraulic head between the soil and the plant root. This line of reasoning has been followed by later researchers including Nimah and Hanks (1973).

Experience with crop yield in saline lands has shown that crop yield is significantly related to soil-water salinity in the root zone (van Genuchten and Hoffman, 1984). To account for this, van Genuchten (1987) proposed a model which accounts simultaneously for the effects of hydraulic forces as well as osmotic forces. Cardon and Letey (1992a) evaluated these two types of approaches by incorporating them into a numerical model and applying the model to field data. They found that under saline conditions the purely mechanistic model of plant water uptake may not be sufficiently reliable because of other important factors influencing plant physiology.

Closely related to plant-water uptake is the crop yield function, which is used extensively in models dealing with economics and management. The maximum yield, Y_{max} , is the crop yield that may be expected under ideal conditions of adequate supplies of non-saline water. Under less than ideal conditions of reduced water supply or increased salinity or both, the yield will be less than Y_{max} . Different crop-yield functions have been proposed in the literature. A discussion of crop yield functions available in the literature has been given by Letey and Knapp (1990).

Leaching the Root Zone

Maintaining optimal salinity in the root zone necessarily implies that excess salt must be

removed from the root zone. On the west side, excess salinity in the root zone poses a particularly challenging problem requiring deliberate management interventions. A common strategy to salinity management is to preirrigate the field during the winter or early spring months to flush salts from the root zone. Growers with unused water supply allocations at the end of the water contracting year have been known to apply large volumes of water to attempt to "bank" water in the shallow groundwater aquifer for the following irrigation season. In the western San Joaquin Valley, dispersion of fine particles and surface sealing of soils decreases infiltration capacity of soils and makes it difficult to meet crop evapotranspiration needs in the latter part of the irrigation season. Obviously, practices such as this, abetted institutionally by the timing of the water contracting year, has exacerbated saline shallow groundwater and drainage problems on the west side. It has been estimated (Salinity and Drainage Task Force, 1992) that deep percolation arising from pre-season irrigation applications alone may amount to 0.5 - 1.0 acre-ft of water per acre per year.

Irrigation engineers have long recognized the need to provide a certain amount of "excess" water to flush accumulated salts from the root zone. Here the word "excess" refers to the amount of water exceeding the ET requirements of the plant. Two important parameters, "leaching required" and "leaching achieved", are used quantitatively by irrigation engineers. A summary discussion of these concepts is provided by Hoffman (1990).

Mathematical models are used by irrigation engineers to generate quantitative understanding of leaching from the root zone. Commonly used models for quantifying leaching needs are based on a mass-balance of water as well as salt in a one-dimensional column of soil, extending from the soil surface through the root zone to the water table. For water balance, these models include rainfall, applied irrigation water, evaporation and transpiration and change in stored moisture as a function of time. The change in the amount of salt in the root zone as a function of time includes the amount of salt imported with the irrigation water, precipitation and dissolution of minerals, salts transported by deep percolation to the water table and the salts removed with the harvested crop. Although conceptually simple, quantified estimation of the various components entering into the equations of mass-balance is extremely difficult. Necessarily therefore, approximations are used to solve practical problems of salinity management in the field. An example of such an idealized model is that of Hoffman and van Genuchten (1983), which uses

a linearly averaged salt concentration for the root zone.

Closely related to the notion of leaching requirement is that of irrigation efficiency. Irrigation efficiency has been defined in many different ways for both practical and policy reasons. One definition of irrigation efficiency is the ratio of the irrigation water applied to the crop to the amount of water beneficially used by the crop. Beneficial use is commonly defined as the annual crop ET or crop water requirement. Some irrigation consultants and agricultural water districts have a broader definition of crop beneficial use which includes a minimum leaching requirement and an allowance for certain cropping practices such as frost protection. The addition of these other factors produces higher estimates of irrigation efficiency since beneficial use is the denominator in the equation. Irrigation efficiencies greater than 100% have been reported by Westlands Water District in areas where shallow groundwater is utilized by the crop to satisfy a portion of crop ET. In such areas the irrigation efficiency, if computed for each irrigation event, shows an increase over the irrigation season as crop roots develop and become extensive enough to intercept capillary water from the shallow ground water table. Calculated irrigation efficiencies are typically lower for individual irrigation events than for the irrigation season as a whole. It follows therefore that depending on whether one considers a single furrow, a single farm or a whole water district or whether one considers a single irrigation event, irrigation over an entire season, or irrigation over the calendar year, irrigation efficiency is a concept subject to spatial as well as temporal scale variations.

Maximizing water use efficiency may not be in the best interests of the grower in circumstances where soils are heterogeneous in their hydraulic properties and where it is difficult to obtain high distribution uniformity of irrigation applications. Burt et. al. (1992) has suggested a practical maximum distribution uniformity of 80% for most furrow irrigation systems. With poor distribution uniformity, high irrigation water use efficiency is not possible if all parts of the field are to be provided with water sufficient to meet crop ET requirements. In some circumstances, such as those which exist in the western San Joaquin Valley, where selenium contaminated drainage is produced in proportion to the excess irrigation applied to the crop, it may become more cost effective to maximize water use efficiency and minimize drainage discharge. This has been demonstrated by Hatchett et al. (1989) using the Westside Agricultural Drainage Economics Model (WADE) where increasing costs of drainage disposal led to

reductions in irrigation applied water. In these circumstances some portion of the field receives less than an optimal water supply - reduced ET then leads to a reduction in crop yield. During the recent drought, water deliveries to growers were reduced by as much as 75% during 1992, which led to a large reductions in irrigated acreage . Water District figures for average crop irrigation applications during the drought period appear to support the conclusions drawn from the WADE model analysis.

Salts, flushed from the root zone are displaced downwards to the water table. The migrating salts displace and mix with resident groundwater and generally act to freshen water quality at the interface between the saturated and vadose zone. Refluxing of shallow groundwater by the processes of evaporative concentration and irrigation flushing increases the salinity of vadose zone water over the irrigation season. Where drains are present, some portion of the saline percolating water is intercepted by the drains and discharged to sumps or surface drainage ditches. Should strong lateral groundwater flow exist below the water table, groundwater salinity may not change significantly because percolating water would continually dilute and displace resident saline water which in turn would migrate and disperse in the direction of the groundwater gradient. However, in the vicinity of the Valley trough where vertical groundwater gradients are minimal and lateral groundwater motion is sluggish, salt concentrations in the shallow groundwater aquifer can build up to high levels owing to frequent refluxing before the water passes below an extinction depth beyond which the effect of evaporative concentration declines to zero. Shallow groundwater salinity can achieve concentrations of between 20 to 30 times the applied water salinity.

Because groundwater is a valuable natural resource in itself, concerns are being raised about the long term viability of the groundwater aquifer as a source of good quality irrigation water. Downward migrating irrigation deep percolation displaces better quality groundwater -- the rate at which this occurs in the upper aquifer is a function of groundwater pumping in the deep semi-confined and lower confined aquifers, which in turn affects the vertical hydraulic gradient in the upper aquifer. To address concerns about irrigation induced salinization of the aquifers, it is necessary to evaluate the relative magnitudes of the effect of practices such as over-irrigation and groundwater pumping. The first step towards achieving this end consists of reducing irrigation deep percolation by minimizing the leaching requirement through effective irrigation

scheduling, choice of irrigation technology and tailoring crop ET needs. In addition, one may manage to maintain as high as possible salt levels in the root zone as will be tolerated by the plants. Letey and Knapp (1990) provide an account of how dynamic programming methods can help in designing irrigation schedules. There are two measures of performance of irrigation application. The first is irrigation efficiency and the second is distribution uniformity as previously discussed. Both these measures of performance can be affected by the choice of irrigation technology (i.e. furrow; drip etc.) as well as irrigation water management that describes the manner in which growers use the technology . Burt et al. (1992) makes the point that without deliberate attempts to improve irrigation management, adoption of new technologies by themselves may do little to improve irrigation water use efficiency. Ayars et al. (1987) described strategies to improve irrigation water use efficiency which include improved irrigation methods, reduction of pre-planting water application, reduction of irrigation as crop nears maturity, partial re-use of drain water and use of on-farm indicators to dynamically guide water application. On the west side, a variety of water application methods are used, including furrow-, corrugation-, basin- and border irrigation methods as well as micro-irrigation methods comprising surface- and subsurface drip irrigation and subirrigation are also used (Kruse et al., 1990). Also, sprinkler irrigation systems used can be divided into permanent, moved, side roll and center pivot.

Water Table Management and Subsurface Drains

It is important to recognize that plant roots may draw water either from above (from applied irrigation water) or from below (upward capillary flow from the water table). Consequently, the shallow water table can be an important source of water to satisfy crop ET needs. Many researchers have recognized the potential of the water table to supply water to the root zone and have investigated the mechanisms involved both theoretically and experimentally. One of the goals of these workers has been to estimate the component of the crop ET needs supplied by the water table. Early work in this regard, based on steady-state unsaturated flow idealization, was carried out by Gardner (1957). Based on carefully controlled field experiments over a 3-year period in North Dakota, Benz et al. (1981) found that maximum crop productivity was obtained when the water table was at an optimum depth of 1 to 1.5 m. Water tables that were too shallow

led to water logging of the plant root and limited the depth of penetration of roots. Grimes and Henderson (1986) found that in areas of shallow water tables, 50 to 60 percent of the crop ET could come from below the root zone directly from the water table. The actual uptake by the plants was found by these authors to depend on the salinity and depth of near-surface groundwater. These authors also found that in order to manage the water table efficiently as a source of crop ET needs, site-specific monitoring and data collection are necessary and a tile drain system should be in place to allow some control of the upward capillary flow.

One of the deleterious effects of supplying water to the root zone from the water table is that salts will be inevitably transported upward to the root zone and subsequently concentrated by evaporative processes and plant water uptake. These salts add to the total mass of soluble salts that must be periodically flushed from the root zone to sustain crop yield.

The ability of water to transport nutrients as well as salts is a fundamental natural process. Therefore, the direction and magnitude of water movement (as governed by hydraulic conductivity) as well as the change in water storage in the root zones (as governed by the hydraulic capacitance of the soil) dictate the rate of removal of salt from the root zone. The dynamics of water movement in the soil is driven by the initial and boundary conditions (which collectively force the system to change), the spatial distribution of materials and the hydraulic properties of the materials themselves. Another important constraint is that salt must be kept below a certain threshold in the root zone. In a sense, this can be viewed as a root zone "salt balance".

Perhaps the most recognized method of controlling and managing the water table is to install subsurface drains to intercept irrigation deep percolation and transport the saline water away from the field. Subsurface drains are no longer made of ceramic tile; rather they are made of perforated flexible plastic and are typically placed at depths varying from 2 to 3 meters (6 to 10 feet) below the land surface on the west side of San Joaquin Valley. The physical nature of the drainage process is such that each drain intercepts water from a zone of influence defined by the soil properties and the depth and spacing of the drains. To intercept a maximum fraction of deep percolation, a system of drains must be laid down at shallow depths at appropriately close spacing. Drainage networks requiring several hundred kilometers of drain lines will be needed if irrigated lands on the order of several thousand acres are to be drained. As an example, Figure

13 illustrates a drainage network in Westlands Water District, comprising field drainage laterals, sumps into which these laterals discharge and collector drains which once conveyed the pumped outflow from the farm sumps into the master collector drain - the San Luis Drain.

As one should expect, drains are most commonly installed in natural groundwater discharge areas and in areas where the water table lies very close to the land surface. Areas with installed subsurface drain networks occupy only parts of each water district. Accurate data on the actual area under drainage on the west side are not readily available because the original drain installation plans have not been regularly updated since initial installation of the drains. In the past growers commonly added to existing drainage networks by installing new laterals equidistant between existing laterals until the desired effect on the groundwater was achieved. Installed drainage systems in the Grasslands Basin, which have been estimated to provide drainage relief to 22,000 hectares (47,820 acres), currently discharge through a network of surface channels and ditches to the San Joaquin River (State Water Resources Control Board, 1987).

Whereas drains in the water districts to the north have historically discharged to the San Joaquin River through a network of shared canals and ditches, Westlands Water District has neither a natural discharge point nor a legal permit that allows discharge to the River. Hence, the construction of subsurface drains within Westlands Water District in the 1970s was coordinated with the construction of a Master Drain for the western San Joaquin Valley -- subsequently named the San Luis Drain. About 5,300 acres of land are underlain by on-farm drains in the Westlands Water District. Prior to 1986, these drains conveyed combined surface and subsurface agricultural drainage to the San Luis Drain. However, these drains were plugged in 1986, following the discovery of selenium toxicity at the Kesterson Reservoir. It is worth noting here that although parts of the area covered by drains in the Grasslands Basin do suffer from elevated levels of selenium, they have been permitted by the CRWQCB to continue functioning, largely because of the ability of the San Joaquin River to dilute salts and trace elements in these discharges to concentration levels that are reasonably close to meeting SWRCB objectives for selenium and boron during wet and normal years. In dry and critically dry years, however, the objectives for boron (and occasionally selenium) are violated most months of the year. Although, at the present time, there is no legal basis for enforcing the standards or for taking punitive action to discourage violations of the objectives from occurring,

Figure 13: Example of tile-drain network, Westlands Water District (A) Plan and (B) Profile. This system has been plugged off, following selenium toxicity at Kesterson (Westlands Water District, 1984)

popular sentiment is that these actions are inevitable in the near future. Water Districts such as Panoche Water District are aggressively seeking ways to decrease their loads of trace elements to the San Joaquin River.

A consequence of the shutting down of the San Luis Drain and the accompanying plugging of the drains of the Westlands Water District is that affected growers have been forced to search for on-farm solutions to manage drainage without any means of disposal outside the district. Some 42,000 acres of land are so affected. One strategy that has resulted from this search is the sequential use of progressively salt-enriched drainage waters and the final disposal of unusable brine into solar salt ponds as recommended by the San Joaquin Valley Drainage Program (1990). Cervinka (1990) has been conducting field experiments on a sequential system in which subsurface drainage water from salt-sensitive crops are used to irrigate salt-tolerant crops, followed by salt-resistant trees such as eucalyptus and finally, halophytes (plants which thrive on salt water) (Figure 14). Although these trees help lower the water table over the first few years, the gradual build up of salts inevitably follows, diminishing the abilities of these plants to extract water from the saline soil environment (Tanji and Karajeh, 1993). Tail water from the halophytes are fed into small, lined experimental evaporation ponds to recover salts, primarily sodium sulfate which has some commercial value. If alternate beneficial use could be found for large quantities of salt residues of evaporation ponds, then lined evaporation ponds may be able to recover their cost of construction with the added benefit that they would prevent contamination of the local groundwater system.

The design and operation of drainage networks is a topic of considerable interest to irrigation engineers. On the local scale, at the farm level, the depth of the drain as well as the spacing is ideally intended to obtain the greatest drainage yield at minimum cost. In practice, installation of drains is limited by the availability of equipment and grade in the field. Over the past decade, researchers on the west side have recognized that lateral flow of water into drains from the groundwater system must be given due consideration in the design of drains (Grismer, 1993). That the drains interact with the shallow groundwater system on the west side has been documented by Deverel and Fujii (1987), Deverel and Fio (1991) and Fio and Deverel (1991). More recent cooperative research between the US Bureau of Reclamation and the Advanced

Figure 14: Successive reuse of irrigation water and agroforestry (From Cervinka, 1990).

Decision Support System Group at Colorado State University (Quinn, 1993) is exploring the effect of retrofitting existing drainage systems to minimize interception of groundwater high in selenium and boron. Where groundwater shows increasing salt and trace element concentrations with depth, shallower, closely spaced drains produce drainage with lower concentrations of salts, selenium and boron. Tailoring the retrofit design to the contaminant depth distribution characteristics in the shallow aquifer at affordable cost may be a viable alternative for irrigated cropland in the Grasslands Basin and perhaps also for the Westlands Water District. In the case of Westlands, minimizing the trace element loading and drainage flow would help reduce the cost of drainage treatment or disposal.

In a project to aid the characterization of shallow aquifer hydrogeochemistry in the Grasslands Basin Ayars and Meek (1994) carried out statistical analysis of water flow and salt load data from the drainage system of the Panoche Drainage District for the period 1986-1991. The analysis showed a strong correlation between drainage flow and load but this relationship tended to be unique for individual drainage sumps. Evidently the combination of deep percolation, shallow and deep groundwater intercepted at each site was different. The apparent stability of this relationship would imply that the majority of tile drainage was displaced groundwater, since deep percolation is more likely to have variable concentration over the irrigation season. Further studies to characterize the drainage systems in the remainder of the Grasslands Basin will be necessary to allow regional management of drainage contaminant loading to the San Joaquin River. This is likely to proceed using a hierarchical systems approach integrating field and modeling studies at the field, district and regional scale.

Site-Characterization

Estimation of hydraulic conductivity, soil-moisture capacity and the dependence of these on soil moisture suction is commonly carried through laboratory tests on soil core samples collected in the field. Traditionally, soil hydraulic conductivity measurements have been made using steady-state flow experiments. Recent research (e.g. Eching and Hopmans 1993, Eching et al., 1994) have tended towards the use of transient experiments, which take into account soil moisture capacitance in the estimation of hydraulic conductivity. In addition, efforts are also made to estimate the hydraulic diffusivity (that is, hydraulic conductivity divided by soil moisture

capacity) in the field on a field scale. Parlange et al. (1993) have developed a technique to this end, based on micrometeorological data.

The greatest challenge to site characterization stems from the ubiquitous spatial variability of the natural soil. Indeed this variability constitutes an unavoidable impediment to the confident application of the principles of physical sciences to the solution of practical problems related to agriculture and irrigation on the west side. The partly ordered and partly disordered distribution of loams, silts, sands and clays in the form of stringers, lenses and layers profoundly influences the patterns of movement of water and solutes within the soil system. As a consequence of spatial variability, these patterns are difficult to comprehend and characterize. Nielsen et al. (1973) and Biggar and Nielsen (1976) carried out detailed field investigations to understand the spatial variability of hydraulic properties, solute displacement and pore water velocities over a 150-hectare field plot. These early studies suggested that field-scale pore velocities are log-normally distributed. These studies also provided insights into the number of field samples that need to be collected to get estimates within a prescribed accuracy and showed that the number of samples needed depends on the nature and extent of spatial variability.

The dynamic processes of flow and transport can be interpreted in terms of Richards equation and the advective-dispersive equation provided that adequate process-relevant data are available on a fine enough scale. Nevertheless, the detailed characterization of the soil features on a scale of a meter or less within a system with dimensions of hundreds of meters is too expensive and not warranted. Therefore, logically consistent and efficient methods must be found by which the effects of small-scale heterogeneity can be incorporated into the larger scale idealizations so that practical problems of farm-level management can be beneficially solved. This challenge has led to two different approaches of problem solving. Some researchers consider the problem of spatial variability to be a formidable one in relation to the resources that can be reasonably invested for their resolution. Accordingly they favor using simple empirical functions for problem solving. One such approach is the transfer function method of Jury et al. (1986) and Sposito et al. (1986). In this approach, simple empirical functions connecting cause and effect are used to characterize the system without giving consideration to process details. Clearly, these functions will be site-specific. Other researchers, seeking to be guided by detailed process-oriented models, choose to use stochastic theory to scale up hydraulic parameters from

a smaller scale to larger scales (Hopmans et al., 1991 and Clausnitzer et al., 1992).

In a recent study, Childs et al. (1993) carefully measured infiltration rates at many points over a 52-acre plot irrigated by furrows using a newly designed furrow infiltrometer. Statistical analysis of the spatial and temporal variations of measured infiltration showed that mean values and variability of irrigation rates could be estimated with data from representative sites rather than resorting to complete field interrogation.

Real-time Monitoring and Instrumentation

The San Joaquin River Management Program Subcommittee on Water Quality, an interagency group including personnel from Lawrence Berkeley National Laboratory, the California Department of Water Resources, the California Regional Water Quality Control Board and the U.S. Geological Survey, have recently embarked on a study to demonstrate the utility of real-time water quality management on the San Joaquin River. The initial phase of the project will require the upgrading of current monitoring stations in the Panoche Water District, in Mud Slough, Salt Slough and along the main stem of the San Joaquin River to allow continuous reporting of electrical conductance (EC), temperature and flow. Radio telemetry is being used to link each of the monitoring stations with a central computer as well as allowing data access to casual authorized users. A second phase of the demonstration project is to estimate selenium and boron loads from the real-time EC and flow data and to develop stochastic short term forecasts of selenium and boron loads from these estimates. Seasonally-based multiple regression models have been shown to improve monthly predictions of selenium and boron loads over annually based regression models. The inclusion of up-river real time flow and EC data will help to improve the reliability of the selenium and boron load forecasts.

Associated cooperative research involving Panoche Water District and the University of Rhode Island is attempting to develop on-farm and district-level strategies that can be employed to regulate the flow of drainage and the drainage selenium and boron loads from the Panoche Water District. These quick-response strategies will involve operating a combination of facilities such as district temporary holding ponds, district recycling pumps and over-riding the current operation of grower operated drainage sump pumps. Ongoing water conservation and drainage recycling programs will further enhance the ability of the district to control drainage exports.

The relevance of this ambitious venture is that it the potential to integrate all knowledge of surface and subsurface hydrological processes from the farm to the regional scale within a single decision support system. Stochastic estimates can be replaced by deterministic models where data are available and the mechanics of the hydrological processes are well understood. To many hydrologists the creation of decision support systems which integrate, in a defensible manner, our current best thinking and best mathematical representations of surface and subsurface hydrological systems, is the major challenge for the next decade.

MATHEMATICAL MODELS

Over the past two decades there has been considerable research on the irrigation and drainage hydrology of the western San Joaquin Valley ranging from micro-level laboratory scale studies to macro-level river basin planning studies. Of these studies few have been successful at modeling the surface and subsurface hydrologic systems with equal rigor. With the large increases in numerical processing power in the past decade this failing has less to do with computing resources and more to do with conceptual limitations, disciplinary bias and short-sightedness. For example hydrogeologists rarely consider irrigation technologies and water management practices in the application of groundwater models; likewise irrigation engineers rarely consider the groundwater aquifer in their models much below the bottom of the crop root zone. An integrative approach is needed since it is certain that models will assume an increased role in river basin planning activities in the future. For purposes of this report, models can be divided into the following groups: process-oriented models, optimization models, planning models and expert systems.

Process-Oriented Models

Process-oriented models seek to analyze the interaction of fluid motion with plant roots and the atmosphere; the transport of heat and dissolved chemical components within the soil; and the chemical interactions which invariably take place between the aqueous phase and the solid phase. Because water ultimately governs the transport of chemical constituents and heat, modeling of water flow is fundamental to all these models.

The equation governing transient flow of water in unsaturated-saturated, deformable media

constitutes the basis for solving the solute transport problems, taking into account advective, dispersive and diffusive processes. Dynamic models combining fluid flow and solute transport, have been applied to study local, farm-level problems as well as regional-scale problems on the west side of the San Joaquin Valley. In addition, chemical reactions between mixing waters and between the aqueous and solid phases are governed by the equations of chemical thermodynamics.

Regional Modeling

In order to gain an understanding of the regional groundwater flow conditions over the central part of the western San Joaquin Valley as a prerequisite for developing drainage management strategies, Belitz et al. (1993) carried out three dimensional, transient groundwater flow simulations using a mathematical model. The area simulated covered 1,410 square kilometers (551 square miles), comprising 11 water districts. In this model, the semi-confined zone overlying the Corcoran Clay was divided vertically into five layers, of which the top two layers were assigned constant thicknesses while the remaining three were assigned spatially variable thicknesses. The confined aquifer was treated as a single layer. The low-permeability Corcoran Clay was represented through a "leakage" term governing the water transfer between the semi-confined zone and the confined aquifer. The simulations accounted for areally variable recharge rates to account for irrigation effects, pumpage from wells, effects of subsurface drain systems and bare soil evaporation. In the horizontal plane, each grid block had an area of 2.56 square kilometers (1 square mile). The hydraulic properties of the materials (hydraulic conductivity, specific storage, porosity and specific yield) were initially assigned on the basis of lithology, data from laboratory tests and data gathered from hydraulic tests conducted in the field. Later, these values were fine-tuned through the model calibration process using field data gathered between 1972 and 1984 from specific sites. Having calibrated the model, Belitz and Phillips (1993, 1995) went on to apply the model to study the response of the system to alternate strategies of irrigation and drainage management.

One finding of this study was that vertical flow predominates in the regional flow system. Based on this findings, the authors infer that deliberate idling of lands or land retirement will have a noticeable impact only in the immediate vicinity of the land. This inference is at variance

with the commonly held belief that upslope irrigators are contributors to down-slope drainage woes.

Belitz and Phillips (1993, 1995) examined alternate management strategies over a 50-year period, 1990-2040. If the status quo were to continue, they infer that the area experiencing bare-soil evaporation will expand from about 575 square kilometers (224 square miles) to about 880 square kilometers (344 square miles) and the flow in the drains will increase from about 3,100 hectare-meter (25,000 acre-feet) to about 345 hectare-meter (28,000 acre-feet). Alternate simulations suggested that by reducing irrigation recharge from 15 to 40 percent and by gradually increasing groundwater pumpage, the area under bare soil evaporation could be reduced to about 200 square kilometers (78 square miles) and drainage flow reduced to about 1,000 hectare-meters (8,000 acre-feet). The authors estimate that some 50,000 hectare-meters (400,000 acre-feet) of water could be released for other beneficial use.

Using the regional model of Belitz and coworkers, Fio (1994) carried out sub-regional scale simulation of groundwater flow and drain interactions over an area largely defined by the boundaries of Panoche water district. Results generated from the regional model provided a basis for specifying the boundary conditions for these simulations. Attention was restricted to the upper 26 meters (85 feet) of the semi-confined zone. This model generally confirmed the results of the regional model in regard to lateral flow but found instances where the vertical flow estimates of the regional model were at variance with field data.

Farm-Scale Modeling

On the local scale, process-oriented mathematical models have been used for a variety of purposes including root zone water movement, water table fluctuations, evapotranspiration, efficiency of irrigation methods, and performance of drain systems.

To study the dynamic interaction between the plants and the water table, Cardon and Letey (1992b) evaluated two types of plant-water uptake equations proposed in the literature (Nimah and Hanks, 1973; van Genuchten, 1987) and concluded that under saline conditions, typical of many parts of the west side, plant uptake models must give consideration to mechanical potentials (Darcy flow) as well as osmotic pressure variations, arising from spatial changes in salinity. Based on this finding, they coupled a form of van Genuchten's (1987) plant-water uptake model

with a one-dimensional transient water and solute transport model (Cardon and Letey, 1992c) to analyze crop yield under dynamic water flow conditions. The credibility of this model was tested by supplying it with detailed data from a well-controlled greenhouse experiment (Cardon and Letey, 1992c).

The efficiency of irrigation at the farm-level is dependent both on the method of irrigation (furrow or sprinkler irrigation) and the uniformity with which water is applied over the field. Using mathematical models restricted to saturated flow conditions. Ben-Asher and Ayars (1990) analyzed the effect of spatial non-uniformity in water application on deep seepage. An important issue addressed in the research is maximization of crop yield since non-uniform irrigation causes deep percolation in some parts of the field and under-irrigation in others. Ben Asher and Ayars (1990) found that more deep percolation resulted from non-uniform sprinkler irrigation than from uniform sprinkler applications.

We have already described the findings of Deverel and Fio (1991) who showed with the help of mathematical models that deeper drains tended to draw a greater portion (as much as 30% to 60%) of groundwater from below. Associated selenium data collected from these sites showed that upward-moving deeper groundwater contributed more to the annual selenium load to the particular drain lateral (332 kg) as compared to the root zone above (68 kg). It is presumed that the selenium captured from the deepest aquifer originated from water that had deep percolated prior to the installation of the drains. We have also seen from the work of Grismer (1989, 1993) "lateral flow" (or regional groundwater flow) is dynamically linked with the flow systems of the drains.

Reactive Chemical Transport

Although many of the process-oriented modeling efforts have been devoted to studying moisture movement and bulk salinity, the importance of understanding chemical reactions which occur between the numerous chemical species within an irrigated system has been recognized by many researchers. These interactions not only involve the mixing of waters of contrasting chemical quality (such as the imported irrigation water, the water in the root zone, and the groundwater) but also the interactions between the water and the solid phases of the soils and the sediments. The chemical interactions are further modified by evaporative concentration and

dilution due to infiltration. These reactions result in profound modifications of the composition of the aqueous phase and the solid phase through precipitation, dissolution, adsorption and desorption. The quantitative analysis of these interactions involving several chemical species constitutes a computational complexity that is far more intensive than the task of modeling moisture movement. Therefore, the application of reactive chemical transport models to the resolution of problems in the west side has become possible only within the past few years, as a new generation of computer work-stations have become available.

Essentially the reactive chemical transport models needed for understanding the behavior of major ions (e.g. Ca, Mg, Na, K, Al, Fe, Si, SO_4 , Cl, HCO_3) and trace elements (e.g. As, Mo, Se, B) are characterized by two attributes. The first is the chemical transformation of the species into various forms (valence states, complexes and minerals) and their addition or removal from the aqueous phase. The second is the transport of the multitude of chemical species by the flowing water. In addition, the chemical transformations are also influenced in a major way by mobile gases (especially in the vadose zone), notably carbon dioxide and oxygen. The chemical transformations include redox reactions, hydrolysis, sorption and ion exchange. These processes are interlinked by the constraints of chemical thermodynamics (electrical neutrality, balance between electron donors and receptors and mass conservation). The transport of chemical species on the other hand, involves processes of advection, molecular diffusion and hydrodynamic dispersion. The task of reactive chemical transport modeling, therefore, entails the dynamic coupling of the transport modules with the various chemical reaction modules.

A quantitative understanding of the interactions between soil minerals and soil water is of fundamental importance for proper agricultural management. Therefore, even with the introduction of rudimentary computers in the early 1960s, soil scientists took the first steps toward applying the principles of equilibrium thermodynamics to interpret reactive chemical transport experiments on soils. Dutt (1962) and Dutt and Tanji (1962) pioneered the practical application of mathematical models for reactive chemical transport when they developed and validated a model for gypsum precipitation in the presence of exchangeable calcium and magnesium. Later, Tanji et al. (1972) applied a similar model to the study of the problem of land reclamation in the San Joaquin Valley. This model simulated, in a credible fashion, the effects of gypsum amendment on sodic soils at eight experimental field plots.

Within the past decade, the availability of powerful computer work-stations has encouraged the development of a number of generic reactive chemical transport models for simulating the simultaneous migration of several chemical components in the presence of fluid-solid interactions involving redox reactions, ion-exchange processes and chemical kinetics. Among the generic models that are available for analyzing fluid-solid interactions one may mention, Felmy et al. (1984), Wolery (1979), Parkhurst et al. (1980) and Mattigod and Sposito (1979).

Simunek and Suarez (1993) have focussed attention on modeling the role of carbon dioxide in controlling the chemistry of the vadose zone and hence, the yield of crops on irrigated lands. Their model couples the temperature-dependent production of carbon dioxide due to microbial action and root respiration and its subsequent transport by transient moisture movement in the unsaturated zone. Suarez and Simunek (1993) applied the model to data from field experiments and found reasonable agreement, thereby supporting model credibility.

Optimization Models

We have seen that process-based models can help evaluate how crop yield and salt-load generation will respond to various strategies of water application and drainage. We have also seen that activities such as leaching, aimed at increasing crop yield may conflict with protection of groundwater quality in the shallow groundwater aquifer in the long term. In addition, these competing objectives are also constrained by economic considerations of cost and benefit. To help make optimal decisions under these conditions, many researchers have applied linear and dynamic programming methods (Knapp and Wichelns, 1990). The decisions involved here may either relate to a single farm or group of farms and consist in identifying the optimal irrigation strategy, giving consideration to crop needs, salinity and the cost of production.

At the farm level, the ideal is to consider several alternative strategies, evaluate the system response to each strategy based on relevant physical-, chemical- and biological processes and automatically choose the particular strategy that is optimal in regard to crop productivity and environmental acceptability. The automatic choice of such a strategy is the goal of dynamic optimization. Unfortunately, such dynamic optimization is computationally intensive, even with currently available computational devices. The feasibility of using dynamic optimization at the farm level over a sequence of years under different choices of crop rotation, spatial variability

and investment in irrigation systems has been demonstrated by Knapp (1992a,b,c). However, when the system becomes complex in terms of interacting physical, chemical and biological processes, dynamic optimization could become computationally impractical. In such cases, the optimization method can be used to screen various options, followed by the evaluation of selected options through detailed process-oriented simulation models already described (Knapp and Wichelns, 1990).

In a recent study, Dinar et al. (1993) have attempted to provide a framework for policy analysis in regard to lands under irrigated agriculture in arid environments, using dynamic programming models as a quantitative tool of analysis. They applied such a model to conditions in evidence on the west side and used empirically observed input functions for crop-yield, salinity and drainage discharge. The objective function in the model consisted of cost and revenue functions. By evaluating alternate strategies for drainage control, they inferred that direct drainage control policies were slightly more cost-effective than indirect control policies. This research also suggested that dynamic models may not always be necessary for this class of problem because under some scenarios, the system under study may rapidly converge to a steady state, eliminating the requirement that time be an independent variable.

Interestingly, optimization models constitute the interface between science-based resource assessment on the hand and resource economics on the other. Agricultural resource economics and associated policy development constitute a very active field of inquiry in the social sciences (e.g. Carlson et al., 1993). Using the physical attributes of resource systems such as soil and water as the basis, researchers involved with economics and policy study how these resources will respond to various strategies of resource utilization and social behavior. Based on such analyses they proceed to understand how, through various strategies of marketing, regulation, incentives and taxation prevalent social behavior can be modified towards a sustained utilization of natural resources. In this context, optimization models constitute an analytical capable of quantifying the complex interactions of a multitude of variables.

The quantified modeling of the economic and social aspects of agricultural- and environmental resource utilization is a task of enormous complexity. On a local scale, at the level of a farmer, economic analysis concerns itself greatly with cost-benefit analysis. On a larger scale, as diverse users compete for available water, the allocation of water, especially

during periods of drought becomes a very difficult task. One approach to overcome this difficulty is to let the market place decide the value each competing user attaches to its needs. For example, an agriculturist with appropriative water rights may trade water to an urban user. Nevertheless, as laid down in the amendment to California's Constitution in 1928, water has to be used for "reasonable and beneficial purposes". As a consequence, economic analysis needs to take into consideration the relative weights that have to be assigned to different segments of society which need water, such as, agriculture, fish and wild-life and urban communities. Clearly, determination of such weights transcend the gamut of the physical sciences.

A discussion of developments in the field of agricultural economics is beyond the scope of the present work. However, in spirit, the present work explicitly recognizes that physical sciences and policy sciences should come together in a rationally sound manner to meet the challenges of San Joaquin Valley agriculture during the coming decades. As a step in that direction, this work presents our current state of knowledge in regard to physical attributes of agriculture in the western San Joaquin Valley and has attempted to show how such knowledge has a bearing on economics and policy related questions.

Regional Planning Models

A category of management models, distinctly different from the process-oriented models described above, is needed on the scale of the west side as a whole. Obviously, these models are broad in scope as they combine resource response with economic objectives. Two important consequences arise from this enlarged scope. First, the number of parameters to be considered become very large due to spatial variability of physical properties, spatial variability of agricultural activities, spatial distribution of economic parameters and so on. Secondly, physical and chemical processes which are defined on the micro scale become less and less meaningful as the spatial scale becomes very large. Consequently, large scale management models have to restrict themselves to fewer parameters, fashioned by combining groups of parameters into fewer lumped parameters, to simulate in a generalized fashion, the most important hydrologic, geochemical and agronomic processes and relationships.

These regional-scale models often use empirical relationships derived from smaller-scale, more detailed models, since models at the regional scale are usually difficult to calibrate and

impossible to validate. These models are commonly used in planning studies which are concerned with comparisons of the effects of a potential future scenario with the effects of a no-action or base condition. Since the basis of these models is comparison rather than prediction, they play an useful role in basin planning as a means of evaluating alternate strategies.

Two examples of planning models among the many models dealing with salinity are the SJVDP West side Agricultural Drainage Economics (WADE) Model (Hatchett et. al., 1989), and the Hydrosalinity Model (HYSAM), Aragues et. al (1990).

The WADE Model was used by the SJVDP to make projections of irrigation technology change and drainage production under a series of policy options and constraints on drainage loading to the San Joaquin River. The model used optimization to determine profit maximizing behavior based on crop revenues and the costs of agricultural production and drainage disposal. Decision variables included crop selection, water supply, irrigation technologies, drainage investment, groundwater pumping, drainage recycling, water transfers between regions and land use. The model discretized the west side of the San Joaquin Valley into cells of between 6800 hectares (15,000 acres) and 18,000 hectares (40,000 acres) in area. Flow between adjacent cells was calibrated against the USGS regional groundwater flow model (Belitz et al. 1991) using a simple Darcy flow assumption and a horizontal conductance term. The WADE Model performed mass balance for flow and salts on the root zone, the shallow semi-confined aquifer, the deep semi-confined aquifer and the sub-Corcoran confined aquifer.

The HYSAM (Aragues and Tanji, 1990) is a simple mass balance model for salt and water that can be applied to an area of any size on the west side of the San Joaquin Valley. Although designed for a single annual time step the model was subsequently adapted to perform sequential annual mass balances and thus simulate salinity transients on the shallow semi-confined aquifer.

Expert Systems

To educate farmers and farm advisors on the effects of improved scheduling and water conservation practices, a graphics-driven expert system was developed for the California Department of Water Resources by California Polytechnic State University at San Luis Obispo. This computer program prompts the user for information on local climate, soil conditions, cropping practices, irrigation technologies employed and the manner in which these technologies

are managed. The user then selects an irrigation application schedule and, using average California Irrigation Management Information System (CIMIS) data, the model plots water distribution uniformity and irrigation efficiency of each seasonal irrigation. In this way the user of the software can experiment with a wide range of management and irrigation options; testing new ideas and management strategies before committing to them in the field. The software is described by its developers as an expert system since it provides the user with recommendations based on his entered field, crop and climatic data and upon their answers to specific management questions posed by the computer program.

The advent of computer graphics and shell scripts for generating easily-understood user-interfaces has greatly enhanced the utility and usability of many simple models for the average computer-literate farmer that previously were strictly the domain of irrigation consultants and university researchers.

ISSUES AND QUESTIONS

GENERAL

The 1990s have ushered in new challenges to irrigated agriculture on the west side. Optimization of agricultural productivity without regard for the environmental consequences is no longer viable. The west side's "natural resource" includes both the quantity and quality of surface waters, groundwater, wetlands, and fish and wildlife habitat. Sustained utilization of these resources in the broader sense entails grappling with issues of resource quantity and quality on several different spatial and temporal scales. Competition between legitimate but conflicting objectives of resource use will necessitate making judgements driven by social and political values, transcending the gamut of science. Problems of agriculture and irrigation can no more be simply resolved by a construction of another reservoir, storage facility or a drain system. Yet, science has to provide to society a carefully documented account of alternatives and consequences, with the understanding that a better-informed society will make a better judgement. Having summarized the current status of our knowledge of agriculture and drainage on the west side, we may now proceed to consider the relevant scientific issues and questions. In particular, we restrict attention to the physical sciences including in its scope hydrology, geochemistry and soil chemistry, soil physics, and related aspects.

It is quite remarkable that the eve of the 21st century, institutions at the local level to the state level and national level (be they industrial, educational or social) are struggling to strike a balance between short-term and long-term objectives. Tangible economic benefits such as return on investment are tied up with issues on a time scale of a year to perhaps a decade. Less tangible are issues concerning sustainability of resource infrastructure and impacts on environment, ecology and society. These issues span a time scale of decades, extending perhaps to centuries. The past decade has seen the growing visibility of the phrase "interdisciplinary research", which reflects the latent recognition by society that the earth is a small planet and all human activities, scientific, technological and social are interlinked. This recognition clearly underscores the need for long-term planning addressing the less tangible issues mentioned above. On the west side of the San Joaquin Valley, the short-term issues typically concern agricultural productivity while the long-term issues are related to potential changes in resource infrastructure, environmental and ecological impacts and social values.

IRRIGATED AGRICULTURE IN A CHANGING SOCIAL CLIMATE

Over California's brief history, alliances have been struck at various times between the major competitors for California's developed water supply. After the California gold rush, when many of California's east side rivers and streams were dammed and used to further hydraulic mining, agriculture in the Sacramento-San Joaquin Delta flourished, followed by agricultural development within the Sacramento and San Joaquin Basins. Agriculture was seen as the driving force for urban expansion in California and both went hand-in-hand culminating in the construction of the Central Valley Project and the State Water Project. Environmental consequences of water development and exploitation became an issue in the 1960's and 1970's creating division between municipal and industrial, agricultural and environmental users of water. In the 1980's the Kesterson crisis and the rising concerns over non-point source pollution in general and pesticides, salts and trace elements in particular demonized agriculture in the eyes of many of the urban coastal communities, eroding the claim irrigated agriculture has had on the lion's share of the State's developed water. The passage of the Central Valley Project Improvement Act (CVPIA) in 1992 witnessed the wholesale transfer of almost 10% of agriculture's share of the State's developed water to environmental interests. Agriculture cannot compete for water supply at

market rates and hence the future will likely witness many more such transfers between agriculture and urban, municipal and environmental interests.

THE FARM-SCALE

Because agricultural productivity depends on the activities at a single farm and because the salinity problem has its source at the individual farm, the farm-scale is a rational starting point for a discussion of issues. As we have seen, the most critical issues on the farm scale pertain to optimal management of moisture, aeration and salinity in the root zone.

Management of root zone salinity involves dynamic processes of moisture movement and geochemistry in the vadose zone, influenced by the water table below, the atmospheric interface above the land surface and imported irrigation water. The coupled physical processes which take place within this system are quite complex. Only within the past decade with the availability of new instrumentation, automated real-time data gathering systems (e.g. Childs et al., 1993, Grismer, 1992) and computers to aid interpretation (Suarez and Simunek, 1993), are these systems beginning to come within the realm of quantitative analysis.

A key parameter in estimating crop yield is the ET requirement. Commensurate with our current ability to gather data in the field and to process these data, simple, empirically formulated ET models are being used to estimate the root extraction function and incorporate them into analysis of moisture-salt dynamics (Nimah and Hanks, 1973; van Genuchten, 1987; Ayars and McWhorter, 1985; Cardon and Letey, 1992a). Improvements in real-time data gathering abilities and interpretation of data should help in the future to obtain a better estimate of ET and plant uptake functions, perhaps as a function of space and time (growth stage). The plant uptake models, at the present level of sophistication, treat the plant root purely as a physical entity, definable in terms of a prescribed moisture potential or osmotic pressure. However, the plant root is a biological entity. It seems likely that future research may help incorporate the biophysical properties of the root directly into root zone hydrologic models thereby going beyond the need to pre-define an ET function.

The plant ET need forms only one component of the dynamic root-zone system. The larger system includes the influx and evaporation of water at the land surface and the fluctuating water table below. The two important issues, namely leaching of the root zone and contribution of the

water table to plant uptake are interrelated within the larger system. Controlled leaching of root salts downward or the controlled supply of water to the root zone upward from the water table are subject to the hydraulic driving forces in the vicinity of the root zone. Although previous workers [e.g. Hoffman (1990), and Grimes and Henderson (1986)] have treated these two as separate issues, there exists a need to integrate the analysis of root zone leaching with water table management in a dynamic fashion.

The advent of coupled geochemical and transport models in the earth sciences (e.g. Simunek and Suarez, 1993, Liu and Narasimhan, 1989) suggests that new quantitative understanding of the hydrogeochemical processes of the vadose zone will be developed over the coming years. Within the vadose zone of an irrigated field, as on the west side, the nature of the geochemical processes will change from season to season. For example, irrigation waters, saturated with oxygen and containing nitrate derived from fertilizers, will introduce a strong oxidizing environment during the growing season. Changing oxidation states of the pore water will influence not only the precipitation and dissolution of redox-sensitive elements such as selenium and arsenic but also the sorption properties of oxide minerals and clays. The work of Suarez and Simunek (1993) has already recognized the importance of coupling carbon dioxide production and transport with transient fluid flow variations in the unsaturated zone. There exists a parallel need to couple the highly transient fluid flow in the unsaturated zone with redox-driven reactive chemical processes. The development of such an understanding will involve a combination of carefully controlled geochemical sampling and soil physical measurements in the field coordinated with the development of new mathematical models capable of combining transient flow of water with dynamically changing conditions of oxidation and acidity within the soil.

It is known that redox driven chemical transformations in the soil are often mediated by microbial processes. Although the importance of microbially mediated kinetics in redox-driven chemical reactions is widely recognized, much new knowledge remains to be gathered on how such processes can be described in terms of measurable field parameters and incorporated into computational algorithms.

It is worth noting here that salinity and drainage problems on the west side are almost exclusively addressed in terms of total dissolved solids and toxic trace elements. Yet, contamination of groundwater by agricultural pesticides is an issue which cannot be readily

ignored. This issue of contamination by pesticides is part of a major investigative effort by the U.S. Geological Survey through its NAWQA (National Water Quality Assessment) Program.

Whether one analyzes just the flow of water or the coupled flow of water and chemicals within the vadose zone in the west side, the spatial variability of soil properties (hydraulic conductivity, soil moisture capacity, porosity) and forcing functions (infiltration, non-uniform irrigation) render the analysis extremely difficult. Under conditions of spatial variability it is necessary to use carefully chosen sampling methods, without which field data may lead to misleading interpretations. Hanson and Grattan (1990) provide a discussion of different sampling methods and their relative merits. Once spatially distributed samples are collected, statistical methods must be used to decipher their spatial correlation structures, if any. These correlation structures will provide clues about the scale in which the data can be reasonably interpreted under conditions of spatial variability. Guitjens and Hanson (1990) summarize available geostatistical methods for interpreting spatial variability in salinity. Stochastic methods have employed by Hopmans et al., 1991) to interpret field experiments involving spatial variability in regard to water flow and salinity. For certain types of processes such as infiltration it may be possible to account for spatial variability by measurements made at carefully chosen locations (Childs et al., 1993). However, it is not certain that all processes may be amenable to simplification to account for spatial variability. Assessing spatial variability of flow and salinity, both in terms of field measurements and in terms of mathematical modeling will continue to be an important issue in west side agriculture.

The issue of spatial variability and scale related to chemical transformations is, as yet, relatively unexplored. Even as we begin to develop chemical thermodynamic models for redox processes and their kinetic modifications, measurement of redox state in the field is known to be extremely difficult. Frequently, careful field measurements reveal the simultaneous presence of aqueous redox couples in a water sample which negate the definition of a single redox state for the macroscopic water sample (Fujii, personal communication, 1993). In systems characterized by such disequilibria, important processes appear to occur at different spatial scales and the identity of these processes may be masked by conventional macroscopic averaging processes. Therefore, to handle this type of spatial variability it may be necessary to formulate new mathematical approaches in which processes occurring at smaller scales are allowed to interact

with those occurring at larger scales; the notion of multiple interacting continua (Pruess and Narasimhan, 1985). Several challenges lie ahead in order to bring a clearer understanding the chemical processes of the vadose zone and permit the sustained utilization of land and water resources on the west side without damage to the environment.

Whereas more and more sophisticated methods are needed to quantify physico-chemical changes in the root zone, the ultimate challenge is to translate the knowledge into strategies of irrigation at the farm level, either for a single irrigation event or for a whole irrigation season. Development of reliable expert systems and decision-making tools to aid farmers and regulators is thus an issue of practical importance. Dynamic optimization models constitute a way of helping resource allocation to competing users for simple systems. For complex systems one may need to use detailed process-oriented simulations with trial and error analysis of alternate strategies before arriving at optimal planning or management decisions. Whatever the approach taken, compatibility between process-oriented models and optimization models are needed in order that the latter may draw upon the most credible input data and the most valid means of characterizing processes. Each farm being unique in regard to soil, hydrogeologic and geochemical conditions, site-specific models need to be constructed for individual farms with the desired goal of a computer-literate farmer being able to run the model and formulate credible resource allocation decisions on the farm. Work along these lines is already being conducted and will continue to play a useful practical role in farm-level decision making.

LINK BETWEEN IRRIGATION AND WATER TABLE

The correlation between continued irrigation on the one hand and rising water table and salinity on the west side is well established. Researchers who have carefully studied the performance of subsurface tile drains in the west side (Deverel and Fio, 1991; Grismer and Woodring, 1987) have shown that drains can capture water by upward movement from substantial depths. Since the major zone of salt contamination on the west side lies between about 10 meters (30 feet) and about 45 meters (150 feet) below the soil surface (Gilliom, 1991) flow paths intercepting water at depths greater than 10 meters (30 feet) can contain elevated levels of salt and trace elements such as Se and B. The recognition of the importance of upward groundwater flow and its consideration in drainage design and analysis on the west side is an

important first step in placing root zone hydrology in the broader perspective of the regional groundwater system. For long-term management of root zone salinity and the water table on the west side it is essential to recognize the relation between the local scale and regional scale groundwater systems. The movement of water in the root zone and in the vicinity of the root zone is dictated by two interacting driving forces; one stems from the regional system driven by recharge on the Coast Ranges and the other by the potential energy of the applied irrigation water at the surface of the irrigated field. Additionally, large scale pumping of groundwater will also influence water table elevations.

In considering the linkage between irrigation water and the water table (which represents the top of the local shallow groundwater system) it is necessary to recognize that local groundwater flow need not necessarily be horizontal (lateral flow). Indeed, as a consequence of regional groundwater hydraulics the local groundwater flow field below the water table could at places be more vertical than horizontal. In addition, zones of stagnation will exist within the flow system. The hydrodynamics of the shallow groundwater system may have significant importance in regard to long-term salinity changes, local hydrogeochemistry and the performance of subsurface drains.

It is known from first principles of regional groundwater motion (Toth, 1963) that the disposition of shallow groundwater systems is sensitive to local changes in physiography. Moreover, in the Valley trough and distal margins of the alluvial fans where discharge areas exist for intermediate and deep flow systems, the potentiometric field driving groundwater motion can be quite complex. Superposed on these complex patterns are the strong impacts of irrigation and evapotranspiration. In order to analyze these systems it is necessary to choose a scale that is larger than the farm scale. At this scale, not only will local physiographic features be given due consideration but also the aquifer characteristics and geology of the semi-confined zone. A need exists to understand groundwater flow systems on a scale that is intermediate between the farm scale on the one hand and the valley-wide scale.

In order that the link between irrigation and the local groundwater system is properly understood, potentiometric and geochemical data should be gathered from carefully designed piezometric nests. Ideally, observations and analyses at this scale will provide a link between the local farm-scale processes and regional, district-wide processes.

Closely related to the linkage of irrigation and the groundwater system is the disposition of the subsurface drainage systems. Drainage configuration, depth and spacing can influence the mixing that occurs of water drawn from the semi-confined aquifer and the deep percolating water above the drain. Inspection of the topology of existing drainage networks can also give clues to the dynamics of flow in the regional aquifer. Many tiled fields are installed using trial and error approach whereby new tile lines are installed between existing lines until the requisite drainage yield is obtained and water tables are stabilized. Hence high drainage densities are indicative of areas of discharge in the regional aquifer. Unfortunately, installation and active pumping of groundwater wells can markedly change a previous stable groundwater regional flow system. Hence drainage topology may reflect a previous groundwater condition prior to installation of the drains and may or may not be helpful in characterizing current regional aquifer flow. Understanding the interactions between the drain system and regional groundwater flow is thus an important issue.

MONITORING SYSTEMS

The time-scale at which a specific control volume within the groundwater flow system responds depends on its position within the groundwater aquifer with respect to the ground surface. Shallow groundwater systems within a few feet of the land surface may respond relatively rapidly on a scale of days to weeks. Groundwater flow patterns at depths in excess of 6 meters (20 feet) may respond on a time scale of weeks to months, while at depths greater than a few tens of meters one may expect changes occurring over tens of years. At any given scale, the rapidity with which the system changes is significantly governed by its capacitance; that is, its ability to take water into storage in response to increasing pressure. Pioneering work related to land subsidence in the west side by Poland and Davis (1969) has shown that fine-grained sediments possess much larger capacitance (storativity) than coarse-grained sediments. The actual change in the nature of the groundwater system in response to irrigation during a given season or over successive seasons will be strongly dependent on the distribution of the fine-grained and coarse-grained materials in the groundwater aquifer as well as changing conditions at the aquifer boundary with the atmosphere such as rainfall, evapotranspiration and irrigation.

To rationally approach the issue of long-term groundwater resource sustainability on the west

side, it would be useful to establish a carefully designed network of piezometer nests which could provide a record of transient groundwater conditions including both flow and water quality. The importance of installing and operating piezometer networks and water quality monitoring wells on the scale of a physiographic unit cannot be overemphasized as a tool to guide decisions that could affect long-term groundwater resource sustainability. Work needs to be initiated on the nature, number and distribution of such monitoring stations and the resources needed to operate them.

It is pertinent to mention here that a wealth of data was collected by the U.S. Geological Survey over nearly four decades on the phenomenon of land subsidence induced by groundwater pumping in the San Joaquin Valley. These data contain much valuable information on the hydraulic properties of the semi-confined aquifer and the confined aquifer and can still be used to help answer questions related to long-term sustainability of the groundwater aquifers and of irrigated agriculture on the west side if supplemented with more recent information. Sadly, current Agency budgets do not include funding for research of this nature.

REGIONAL SALT BALANCE

To achieve long-term resource sustainability on the west side, the problem of salt accumulation in the regional groundwater system must be reversed or at the very least diminished. Salts that cannot be disposed of to the river from west side agriculture must be managed within the Basin. Salts remaining in the Basin may be stored in the root zone, flushed into the shallow groundwater aquifer, drawn into the deeper aquifer by high vertical gradients and recirculated to the surface through groundwater pumping. Salt storage decisions are made at different time scales. On the time scale of an agricultural irrigation season, management decisions have to be made on the disposal of subsurface drainage. On a time scale of decades, decisions may have to be made to retire certain lands that are salinized beyond the point of economic recovery owing to inadequate drainage or because of competing commitments for water deliveries, competing water requirements of wetlands and in-stream flows and to satisfy increasing municipal and industrial requirements. In theory, agricultural productivity on the west side could be maintained indefinitely if the salt load imported into the San Joaquin Valley was equal to that exported, assuming an equal and even distribution of salts within the system. In

practice, however, this goal is likely unattainable, largely because of economic, legal and institutional constraints and the tremendous heterogeneity of soil and water resources within the system.

What is likely is that over the next several decades the region may attain some sort of steady state in which a constant, net quantity of salt is imported into the region each year. For example, Orlob (1991) estimates that by the year 2007 the annual importation of salt load will remain approximately steady at about 2 million metric tons over the entire Valley, if the current trend continues. The basic question then is how and where this excess can be stored or disposed of so that the root zone is maintained at an optimal salinity and the groundwater aquifer maintained such that the quality of agricultural pumpage is unaffected. Current trends are of increasing salt concentration in agricultural pumpage in many parts of the Basin.

As we have seen, problems of rising water table and salinity build-up are characteristic of the lower parts of the Valley (the trough). The build-up of salt in the lower parts of the west side can be divided into two major components: (a) dissolved chemicals transported by regional groundwater flow and (b) salt dissolved in the water imported via the Delta-Mendota Canal and the California Aqueduct. Let us consider each of these.

(a) Regional groundwater flow. The regional groundwater system is largely driven by the topography of the Coast Ranges and of the west side. As can be seen in Figure 6, the land slopes more or less to the ENE over the entire area of the west side. Conforming to this topography, groundwater moves from the recharge areas on the west to the ENE, towards the Valley trough and the San Joaquin River. Mean groundwater accretions along the main stem of the San Joaquin River have been estimated to be approximately 2 cfs/mile occur. Flow is greater from the west side where water tables are marginally higher than on the east side where water tables are more influenced by high levels of groundwater pumping along the upper reaches of the main stem of the river. Groundwater flow occurs within the Sierran Sand aquifer beneath the Valley trough, from west to east, in response to a groundwater gradient, generated by east-side pumping (Belitz, 1991). In contrast, flow within the confined aquifer beneath the Corcoran Clay appears to be in the opposite direction, from east to west, in response to the large volume of groundwater pumping in the upslope areas of the west side.

(b) Water supply imported from the Delta. Despite the fact that this water is of excellent

quality and relatively low in dissolved salts, the volume of water is so large that the total salt load imported and broadcast on west side agricultural lands is immense. Orlob (1991) estimated that between 1930 and 1990, the net accretion of salt due to irrigated lands on the west side of the San Joaquin Valley amounted to about 75 million tons.

It is now appropriate to examine the fate of this accumulating salt. If we go back to the early 19th century, a major source of salts in the lower parts of the Valley (that is, the trough) would have been transport associated with regional groundwater motion. Part of this load was evaporatively concentrated, part of it was transported and stored in the semi-confined groundwater aquifer and part of it migrated to San Joaquin River, where it mixed with in-stream flows and discharged to the Delta.

Following the introduction of irrigation and its rapid adoption within the San Joaquin Valley, salts imported with irrigation supply have been added to those transported by regional groundwater motion. The pre-irrigation mass balance of salts in the San Joaquin Basin has been greatly perturbed. The ultimate long-range issue of salt-load management in the San Joaquin Basin is this. Given those factors affecting agricultural sustainability which constrain the accumulation of salt in the Basin, and given an annual constraint to the assimilative capacity of the San Joaquin River, how may one manage the excess salt load?

Early in the 1960s the Bureau of Reclamation as well as the State of California did envisage a master drain (the San Luis Drain) to export all excess salts to the Delta and ultimately to the Pacific Ocean. However, the operation of such a Drain has been obfuscated following the Kesterson experience of the early 1980s. Hence, at the present time, the export of salts and trace elements agricultural drainage is restricted to the San Joaquin River, to the limits of the River's assimilation capacity. The assimilative capacity of the San Joaquin River is currently determined by a Vernalis EC standard of 0.7 mmhos/cm during the critical irrigation period and 1.0 during the non-irrigation season for downstream users such as the South Delta Water Agency. The Bureau of Reclamation is required to make releases from New Melones Dam so ensure that in-stream water quality does not exceed these standards. As a means of addressing the salt balance issues, a pipeline to the ocean was investigated by the SJVDP. Although the scheme was technically reasonable, it proved unacceptable for social and political reasons, even before the studies on its cost and possible alignment had been completed.

The plugging up of drains over an area of roughly 2,150 hectares (5,300 acres) in the Westlands Water District to eliminate selenium contaminated drainage from Kesterson Reservoir has led to a pressing need to find in-Valley solutions for the disposal of agricultural drainage. As a result, re-use of agricultural drainage and the blending of agricultural drainage to irrigate salt-tolerant crops has increased. Drainage return flows arising after such re-use is being used to grow salt-tolerant trees. Some return flows from these areas are discharged to evaporation ponds where these are available. Presently, there is a moratorium on the construction of new evaporation ponds on the west side due to problems of bird safety.

The fact that the zone of high salinity and trace element contamination has migrated to between 20 and 50 meters (60 and 150 feet) of the land surface (Gilliom, 1991) is an indication that the groundwater system is storing salts generated by long-term irrigation. Letey and Oster (1993) analyzed recent data pertaining to rates of water table rise on the west side and concluded that by allowing the water table to remain close to the root zone one may not only supply a good part of the plant ET from the water table (thereby reducing irrigation needs) but also encourage increased leakage between semiconfined and confined aquifers through the Corcoran Clay. Based on estimates of vertical hydraulic conductivity of Corcoran Clay, they reason that deep leakage will help maintain a more or less steady, shallow water table over long periods of time. They also suggested that it is necessary to evaluate the relative merits of storing salts in the groundwater system over extensive areas as opposed to disposing of large quantities of salt in small areas through evaporation ponds.

Although Letey and Oster (1993) have done well to focus attention on the importance of the role of the groundwater system in regard to salt management, it seems necessary to recognize that the transient response of the semi-confined zone to irrigation is likely to be complex. The semi-confined zone on the west side varies in thickness from 125 to 300 meters (400 to 900 feet) and comprises both fine-grained and coarse-grained sediments derived from the Coast Range. In the lower part of the Valley, coarse-grained sediments derived from the Sierra Nevada Mountain Range also exist. Available geological knowledge suggests that the fine-grained sediments (clays, silts and sandy clays) occur intermixed with coarse-grained sediments such as gravel, sand and silty or clayey sands and gravels). The heterogeneous system appears to consist of a complex system of layers, lenses and stringers of different parent materials. Because of their shallow,

unconsolidated nature, the fine-grained sediments tend to be highly compressible and hence characterized by high specific storage (hydraulic capacitance).

As a consequence of the sloping topography of the west side and the complex system of layers, lenses and stringers, the flow pattern within the semi-confined zone is likely to be characterized by lateral subhorizontal flow paths in the coarse-grained units and vertical flow paths within fine-grained units. Moreover, because of the presence of compressible fine-grained sediments, the manner in which the effects of fluctuating water table propagates downwards to the Corcoran Clay could be quite complex in space and in time. It is likely that the effects of a fluctuating water table would be damped by the compressible formations within the semi-confined zone. An understanding of how the effects of managing the water table propagates down through the semi-confined zone, causing changes in groundwater storage in the fine-grained sediments is of fundamental importance.

Even more important is to understand how the salinity front moves downwards through the heterogeneous semi-confined system over a long period of time and how rapidly water quality of the deeper parts of the semi-confined system decreases over time. Careful and continuous monitoring of potentiometric heads in piezometer nests installed at carefully chosen locations are crucial for this purpose. Installation and maintenance of such observation stations distributed over the west side must be considered an intrinsic part of the long-term management strategy for the west side of the San Joaquin Valley.

CONJUNCTIVE USE OF WATER

It stands to reason that conjunctive use of groundwater will greatly aid in managing the hydrologic regime in the vicinity of the root zone. Clearly, groundwater pumpage could help lower the water table and alleviate a need for drainage. Apart from the fact that such a lowering of the water table will reduce the availability of plant ET from the water table, the relation between water table fluctuation and water pumpage in a large heterogeneous system with highly compressible aquitard materials is complex. If the water table is to be managed over large areas, the number of wells required, their distribution, depth and the schedule of pumping would be site-specific. For this purpose it would be necessary to hydraulically characterize the semi-confined zone in a much greater detail than has been attempted to date.

Furthermore, it is important to recognize that large-scale pumping of water from above the Corcoran Clay will have two important consequences. First is the potential for land subsidence arising from the slow compaction of fine-grained sediments. The second consequence is that the drop in potential in the semi-confined zone will profoundly influence leakage through the Corcoran Clay (Belitz and Phillips (1993, 1995)).

VALLEY-WIDE WATER MANAGEMENT

The management of irrigation water deliveries, drain systems and the chemical quality of the agricultural return flows on an inter-district water scale is an issue of relevance to institutions such as the Bureau of Reclamation, the California State Water Resources Control Board, the California Department of Water Resources, the California Regional Water Quality Control Board, and the State Legislature. These agencies require the use of workable tools not only for operational purposes but also for long-term planning purposes.

The Bureau of Reclamation and the California Department of Water Resources are the responsible Federal and State agencies concerned with water resource planning in the San Joaquin Valley. The most significant planning decision, made annually, that affects the agricultural productivity of the land resource and the environmental quality of riverine and groundwater resources is water allocation to Federal and State water contractors. These decisions are made with the help of mathematical models which perform monthly accounting calculations matching water demands with available developed water supply in the CVP and SWP reservoirs, mostly located in the Sacramento Valley. During times of drought, water deliveries to water districts are cut back, leading to fallowing or reduced irrigation applications to large areas and increased groundwater pumpage in the San Joaquin Valley and on the west side in particular, which relies most heavily on imported Delta water.

MATHEMATICAL MODELS

The inter-relationships which exists between the natural groundwater flow system and irrigation activities on the land surface have not been adequately captured in any mathematical simulation model of the western San Joaquin Valley or the San Joaquin Basin to date. To make rational decisions which might help us achieve long-term sustainability of surface water and

groundwater resources on the west side, we need to think of an active, large system with several essential interacting components. The operation of this system has to be continuously fine-tuned. Such a fine-tuning has to rely on two major efforts: monitoring and modeling.

A complex and dynamic natural system continuously evolves. Some parameters of the system can only be estimated with adequate data in the time domain while other parameters may change with time. Therefore a network of monitoring stations to continuously observe the hydrogeological and hydrogeochemical attributes of the system is an essential integral part of long-term planning for the west side.

On the side of interpretation and forecasting, it is essential that adequate interpretative tools are available to interpret the monitored data. At the present time, computer-based numerical models constitute the best interpretative tools for the purpose. Therefore, assembling a set of relevant computational tools is an issue of major importance. As we have seen, problems of interest vary in scale from that of a single farm to the Valley as a whole. In the time domain, the scale of interest may vary from a single irrigation event to several decades. On the small scale, process-oriented models for water movement, heat transport and reactive chemistry are important. On the largest scale, operation of distribution networks play a more important role than process-specific details. Yet models between the extremities must be compatible with each other so as to provide and receive vital information. One way to achieve such an end is to think of a hierarchy of inter-related models, linking issues on all spatial and temporal scales.

As we look to the sustainability of irrigated agriculture on the west side at a time of global competition in agriculture, the acceptance of the need to maintain a healthy environment in California and a rapidly increasing population, the following issues are relevant to irrigated agriculture on the west side.

SHORT-TERM PRODUCTION-ORIENTED ISSUES

- Evaluation of crop ET needs as a function of changing conditions of soil moisture and salinity.
- Design of irrigation scheduling and application methodology based on changing soil physical conditions, crop ET needs and disposition of local water table.

- Incorporation of information on spatial variability of soil properties and topographic changes into techniques for evaluating crop ET needs as well as the design of irrigation schedules and water application methods at the farm level.
- Development of optimization models on a time scale of seasons to integrate irrigation practices, cropping patterns and economics.
- Integrated operation of drainage-networks (Grasslands District) to discharge effluents into the San Joaquin River at times of high assimilative capacity to comply with water quality standards prescribed at downstream locations. The impact of these operations on the long-term changes in selenium accumulation in the San Francisco Bay.
- Development of real-time monitoring instruments and data transmission equipment at the farm level as well at regional levels to provide data for estimating crop ET needs, irrigation scheduling and management of drainage networks.
- Improved methods of water reuse, crop selection and agro-forestry in portions of Westlands Water District where no natural outlet exists for disposing drainage effluents and where trace element contamination is a more serious problem than salinity.
- Conjunctive use of groundwater and surface water to manage water table elevations and reduce drainage volume and contaminant loads.
- Extension of the useful life of pumping wells by controlling groundwater degradation.
- Assessment of the potential for real-time monitoring and deployment of improved information transfer technologies to reduce drainage volumes and contaminant loads.
- Development of cost effective techniques to control erosion and sediment transport from the intermittent streams of the Coast Ranges, which periodically deposit large volumes of selenium laden sediments on agricultural lands situated on alluvial fans.

LONG-TERM SUSTAINABILITY ISSUES

- Assuming that the San Joaquin River is the only outlet available for exporting saline effluents, the rate at which net salt accumulation will accrue on the west side even under the most efficient water use scenarios.
- The extent and depth to which the groundwater system has been contaminated by past agricultural practices.

- The nature and the time scale of coupling between the irrigation system, the regional groundwater system and regional pumpage. The time rate at which irrigation-mobilized contaminants propagate through the groundwater system.
- The relationship between pumpage from aquifers above and below the Corcoran Clay and the potential for induced contamination of the deep aquifers across the Corcoran Clay through irrigation wells.
- Determination of the hydrological and geochemical linkages between irrigation, drain-networks and the regional groundwater system on a scale of topographic or physiographic units.
- Delineation of areas where land degradation occurs irretrievably and the implications for land retirement, contract renewal and long-term land management.
- Developing monitoring programs to systematically monitor the long-term response of the land and the groundwater system to irrigated agriculture.
- In the context of justifiable environmental concerns and growing urban needs for water, to develop methods for determining the "net public good" emanating from agriculture on the west side and to explore the economics of conversion of irrigated land to other beneficial uses.
- Resolution of water policy issues. If, according to the amendment of California's constitution of 1928 all water in California must be used for reasonable beneficial purposes, can users of water trade their quotas for money? Or, should they forfeit the allocation of water if it is not used for the purpose for which it is intended?

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