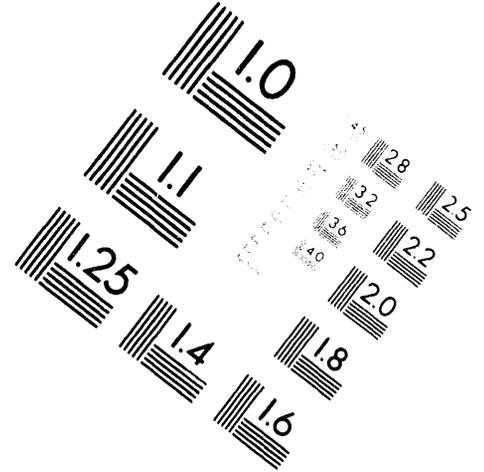
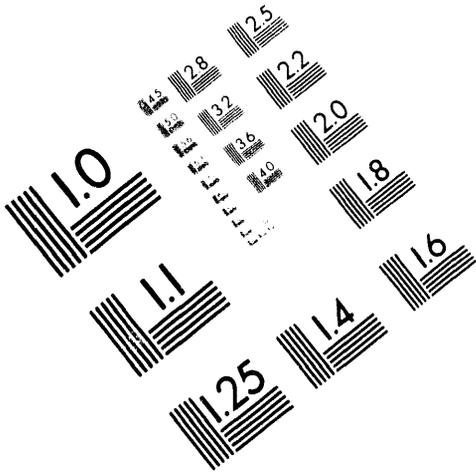




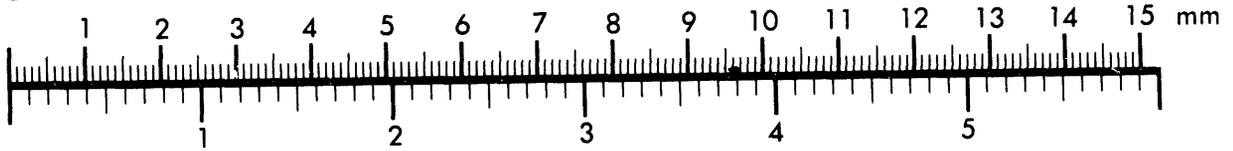
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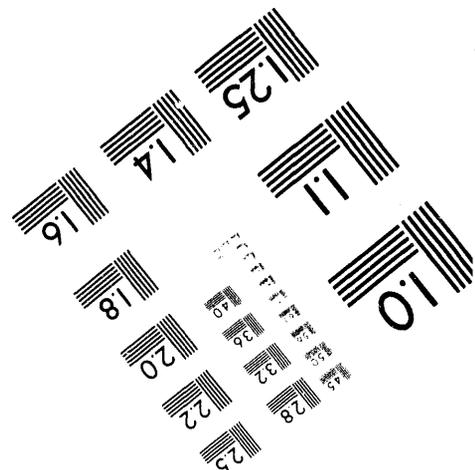
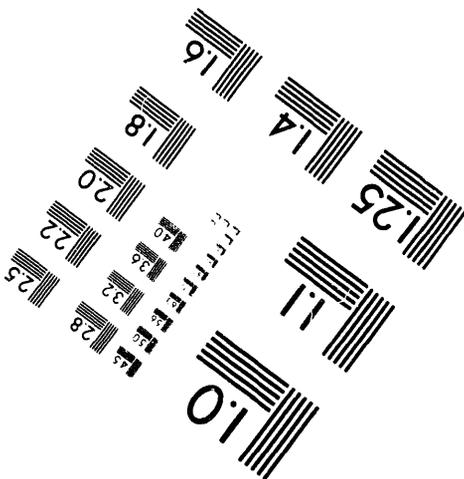
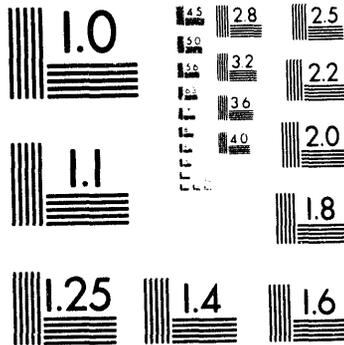
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Issues of Sustainable Irrigated Agriculture in the San Joaquin Valley of California in a Changing Regulatory Environment Concerning Water Quality and Protection of Wildlife.

Nigel W.T. Quinn, PhD
Staff Scientist
Earth Sciences Division
Lawrence Berkeley Laboratory
University of California, Berkeley
1 Cyclotron Road, Berkeley
CA 94720, USA.

and

Michael L. Delamore
Chief, Water and Power Resources
U.S. Bureau of Reclamation
2800 Cottage Way, MP-405
Sacramento, CA 95825, USA.

June 28-30, 1994

This work was supported by the U. S. Bureau of Reclamation under the U.S. Department of the Interior Interagency Agreement No. 0-AA-20-09410, through U.S. Department of Energy Contract No. DE-AC03-76SF00098.

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Nigel W.T. Quinn

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California, Berkeley
CA 94720, USA.

Michael L. Delamore

U.S. Bureau of Reclamation
2800 Cottage Way, MP-405
Sacramento, CA 95825
USA.

Summary

Since the discovery of selenium toxicosis in the Kesterson Reservoir on the west side of the San Joaquin Valley, California, public perception of irrigated agriculture as a benign competitor for California's developed water supply has been changed irrevocably. Subsurface return flows from irrigated agriculture were implicated as the source of selenium which led to incidents of reproductive failure in waterfowl and threatened the survival of other fish and wildlife species. Stringent water quality objectives were promulgated to protect rivers, tributaries, sloughs and other water bodies receiving agricultural discharges from selenium contamination. Achieving these objectives was left to the agricultural water districts, federal and state agencies responsible for drainage and water quality enforcement in the San Joaquin Basin. This paper describes some of the strategies that have been investigated to improve management of water resources and water quality in the San Joaquin Valley to respond to these new environmental objectives. Similar environmental objectives will likely be adopted by other developed and developing countries with large regions of arid zone agriculture and susceptible wildlife resources. Some are doing so already. A series of simulation models have been developed over the past four years to evaluate regional drainage management strategies such as: irrigation source control; drainage recycling; selective retirement of agricultural land; regional shallow ground water pumping; coordination of agricultural drainage, wetland and reservoir releases; and short-term ponding of drainage water. A new generation of decision-support software is currently under development to bridge the gap between planning and program implementation. This decision support system for drainage management is Geographic Information System (GIS)-based and uses

graphical user interfaces to promote correct application of the software. Use of the decision support system will allow water districts and regulators to continuously monitor drainage discharges to the San Joaquin River in real-time and to assess the impacts of management strategies that have been implemented to take advantage of the River's assimilative capacity for trace elements and salts.

1. Introduction

The last decade has witnessed an escalation in the frequency of conflicts between agricultural consumers of water, municipalities and environmental interests in the San Joaquin Valley of California. One hundred years of agricultural expansion within the San Joaquin Valley has been blamed for a significant loss of native wetlands and wintering habitat for wildfowl and other wildlife species. In addition, operations of the major pumping stations, reservoirs and canals (which comprise the Federal and State Water Projects and which provide hydropower, irrigation, municipal and industrial water supplies) threaten native fisheries within many of California's major streams and rivers. Increasing pressures of urbanization currently threaten both agriculture and the environment as developers provide homes for an increasingly burgeoning population.

However, it was the selenium contamination crisis at Kesterson Reservoir on the west-side of the San Joaquin Valley that helped spark wide-spread public interest in irrigation-induced environmental problems. Selenium toxicosis at Kesterson Reservoir was attributed to evapo-concentration of agricultural drainage in terminal evaporation ponds. Selenium had been leached from surface soils into the ground water over decades since the onset of irrigated agriculture. Ever since, naturally high levels of selenium in the western San Joaquin Valley and other western states have been the focal point of complex and contentious issues concerning the management of irrigation drainage. Selenium toxicosis may be the "tip of the iceberg" as science improves in its ability to detect causality between activities such as irrigated agriculture and damage to critical habitat for fish, wildfowl and other wildlife because of contaminants (such as certain trace elements, heavy metals and non-synthetic organic compounds).

Increasing calls by environmental and other interests over the past decade for legislative reform of water allocation within California culminated in

passage of the Central Valley Project Improvement Act (CVPIA) of 1992. This landmark Act rivals the Reclamation Act of 1902 (which promoted the development of water resources in the western United States) and the National Environmental Protection Act of 1970 (which institutionalized consideration of environmental effects in all water management and development actions) in its impact on water resource allocation. The Act reallocated approximately 10% of the developed water supply of the State from agricultural uses to fish and wildlife uses as well as to other environmental purposes. Listing of fish species under the Endangered Species Act, including the Delta Smelt, a fish found only in the Sacramento-San Joaquin Delta, has made it increasingly difficult for the CVP Delta pumps to make full water deliveries, even in wet years. Hence agriculture is challenged to develop new strategies for managing its reduced allotment of the State's water resources, while sustaining its' profitability and minimizing impacts to the environment. Increased conjunctive use of groundwater resources will likely decrease the quality of agricultural return flows and make compliance with water quality objectives more difficult. Improvements in river and drainage management through the application of real-time, decision support systems presents an opportunity for agriculture to meet newly legislated environmental objectives without great expenditure and with minimal environmental impact.

2. Irrigation induced water quality problems in the San Joaquin Valley

The western San Joaquin Valley is arid, receiving too little rainfall to make commercial agriculture viable without supplemental irrigation. Alluvial deposits, from which much of the Valley soils are derived, are marine in origin and are mostly high in native salts and trace elements such as boron and selenium. The downward displacement of native salts, that had accumulated at the soil surface, was greatly accelerated by the expansion of agricultural irrigation, starting with the invention of the deep turbine pump in the 1920's. Infiltrating water dissolves and leaches these salts and trace elements into the shallow ground water, a necessary consequence of maintaining salt balance in the crop rooting zone. Without adequate drainage, water tables in irrigated areas tend to rise leading to waterlogging and evapo-concentration of salts and trace elements in the crop root zone, making salt balance more difficult to achieve. When salts accumulate in the root zone crop

yields of salt sensitive crops decline, eventually leading to a situation where the costs of production exceeds the income derived from crop sales, resulting in the eventual abandonment of the land for irrigated agriculture.

Of the estimated seven million tons of salt that are added annually to soils in the San Joaquin Valley, approximately half is derived from water imported through the Federal Central Valley Project (CVP) and the State Water Project (SWP). Authorization of the San Luis Unit of the CVP on the west-side of the San Joaquin Valley included the construction of a drainage facility to collect saline drainage water from the irrigated service area. However, a final point of discharge for the planned drainage facility has never been identified and the partially-built San Luis Drain terminated at Kesterson Reservoir. Agricultural surface and subsurface drainage originating from the Grasslands Basin has always flowed through a network of canals, ditches and sloughs to the San Joaquin River. Agricultural land to the south of the Grasslands Basin has no natural outlet and its drainage from approximately 2000 hectares of these lands, passed to Kesterson Reservoir along the San Luis Drain during the period from 1978 to 1985, that caused the selenium toxicosis problem. Prior to the observation of the wildfowl reproductive failure, joint use of Kesterson as a drainage regulating reservoir and a wildlife refuge appeared to be mutually advantageous. The consequent plugging of the subsurface tile drains that discharged into the San Luis Drain has reduced drainage options for farmers in the affected area. Selenium drainage problems similar to those at Kesterson have been observed in evaporation ponds in the southern San Joaquin Valley and in drainage ponds throughout the western United States. A reconnaissance of selenium drainage problems in other arid zones around the world has yet to be performed - the results of such a study may reveal similar environmental impacts to those experienced in California.

In the Grasslands Basin, agricultural land subjected to shallow saline ground water produces drainage with high concentrations of dissolved solids, selenium and boron. At the present time, stringent SWRCB San Joaquin River objectives for boron and selenium at the Newman monitoring site, and for salt at the Vernalis site, (Figure 1) are frequently exceeded. A water quality objective for receiving waters of 5 ppb (2 ppb for water supply to wetlands) was established for selenium, based on toxicity to fish and wildlife species. The boron objective was set at 2 ppm to protect agricultural yields. A

SAN JOAQUIN RIVER SYSTEM

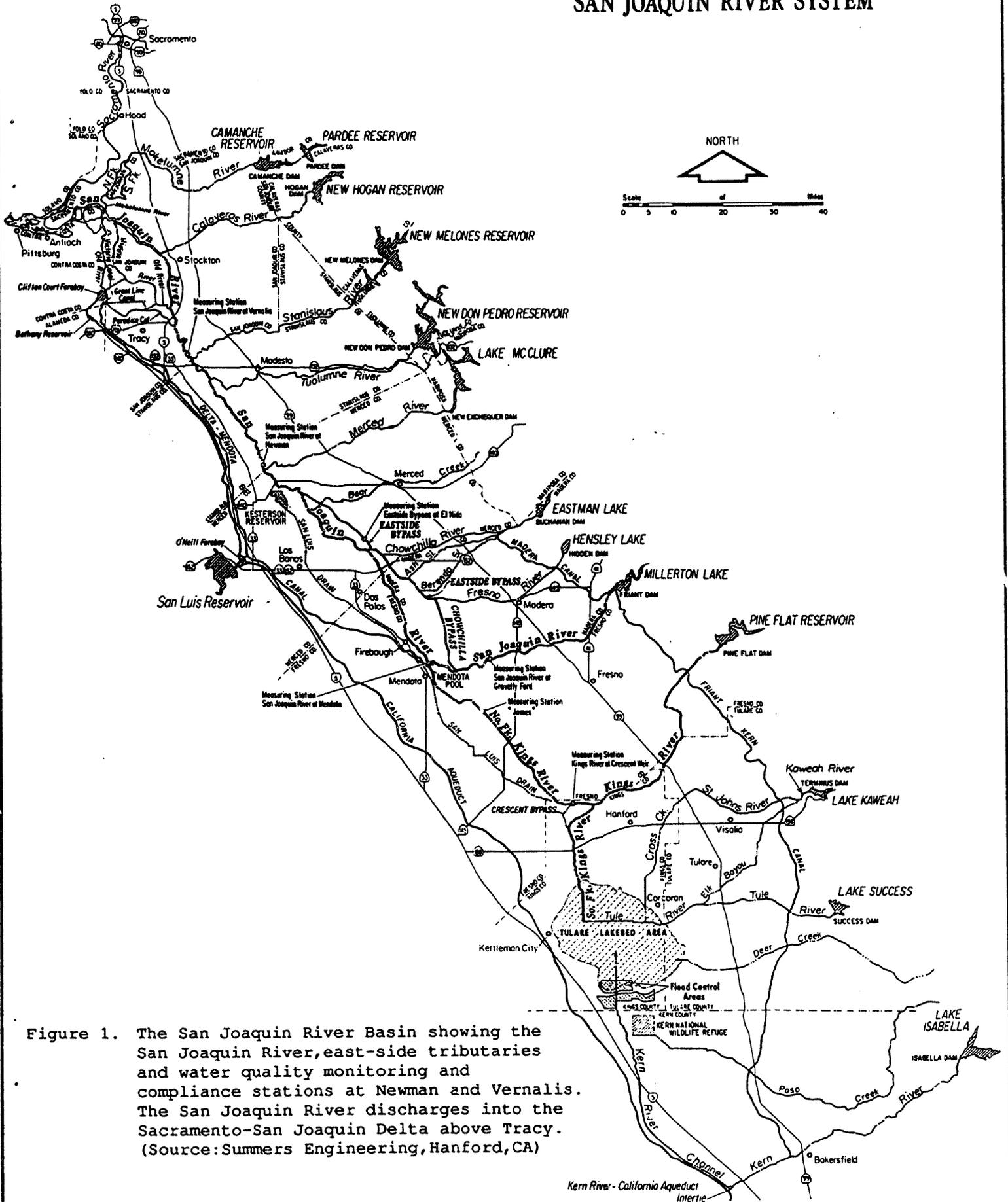


Figure 1. The San Joaquin River Basin showing the San Joaquin River, east-side tributaries and water quality monitoring and compliance stations at Newman and Vernalis. The San Joaquin River discharges into the Sacramento-San Joaquin Delta above Tracy. (Source: Summers Engineering, Hanford, CA)

salinity objective of 590 ppm TDS (410 ppm during the irrigation season) has been recommended for Vernalis to protect water quality for downstream agricultural users. Salts and trace elements carried by the San Joaquin River into the Sacramento-San Joaquin Delta affect the quality of irrigation diversions and can constrain water deliveries from the Delta to agricultural and municipal customers in the San Joaquin Valley and in Southern California. The supply of water exported south from the Delta pumping facilities is further constrained to minimize fish entrainment during migration periods.

During the spring months a combination of wetland releases in the Grasslands Basin and agricultural subsurface drainage combine to increase both the average concentration and the total mass loading of salt, selenium and boron, within the San Joaquin River. At other times of the year, reservoir releases made for flood control, recreation, power and to assist fish migration reduce selenium and boron concentrations to levels well below water quality objectives for the San Joaquin River. Better coordination of drainage operations and reservoir releases, brought about through real-time monitoring and information linkages between decision makers, could help to maximize contaminant export to the river without violating environmental loading limits. Recent studies have demonstrated that irrigation season reductions in drainage contaminant loading will be necessary, in dry and critically dry years, to avoid violating SWRCB water quality objectives (Quinn,1992).

An examination of various management options for reduction of contaminated drainage loading to the San Joaquin River and compliance with water quality objectives recommended control of drainage at its source, to the maximum extent possible, as the most practical strategy (SJVDP,1990). Source reduction strategies included: improvements in irrigation scheduling, implementation of tailwater and drainage recycling, adoption of improved irrigation technologies such as surge irrigation, gated pipe, sub-surface drip irrigation and shortened furrow lengths and changes in cropping practices to deeper rooted, more salt tolerant crops. Other techniques were recommended including drainage reuse on tree crops such as atriplex or eucalyptus as short to medium term measures, which help to reduce the volume of contaminated drainage requiring disposal; regional pumping of shallow ground water to lower high saline water tables and selected land retirement to control regional water tables and reduce the interception of contaminated ground water by tile drains.

3. Integration of screening models to assess real-time drainage management

Coupled with source control and drainage management measures mentioned, long term compliance with water quality objectives and maintenance of salt and water balance in the crop root zone can be facilitated by real-time management of river and drainage flows. The first step in creating a decision support system for drainage management was the integration of a series of computer-based screening models (Figure 2). Direct reduction of drainage loading increases operational flexibility of a real-time drainage management system. Using monthly time series data this system of models simulates various aspects of San Joaquin Basin drainage hydrology and water quality. Fifty years of continuous flow data are available for flow gauging stations along the San Joaquin River and along major tributaries. Water quality data includes discrete selenium and boron samples and continuous electrical conductivity records, collected since 1984.

An effort has been made to link these models either directly or indirectly through the use of a common spatial database creating a data-centered architecture for the system of planning models. Work is continuing to develop graphical user interfaces (GUI's) for the series of models illustrated on the left side of Figure 2.

The **San Joaquin Area Simulation Model (SANJASM)** was developed by the USBR to simulate water supply allocation decisions in the San Joaquin Basin. The model is data driven and simulates reservoir releases down each of the major tributaries of the San Joaquin River which are subject to reservoir operating rules for flood control, fish flows, power production and contractual delivery schedules. The logic built into the model emulates USBR and Corps of Engineers (COE) release decisions from the major reservoirs on each tributary to the San Joaquin River, using either historic or synthetic reservoir inflows. Reservoir operating rules account for different runoff year types using the San Joaquin River Basin four-river index. These rules affect irrigation water supply, fish and in-stream flows, and reservoir releases to meet water quality criteria. In the absence of real-time release information SANJASM provides the most complete estimates of San Joaquin River flows.

The **San Joaquin River Input-Output Model (SJRIO-2)** was developed by the SWRCB to assist in the promulgation of San Joaquin River water quality

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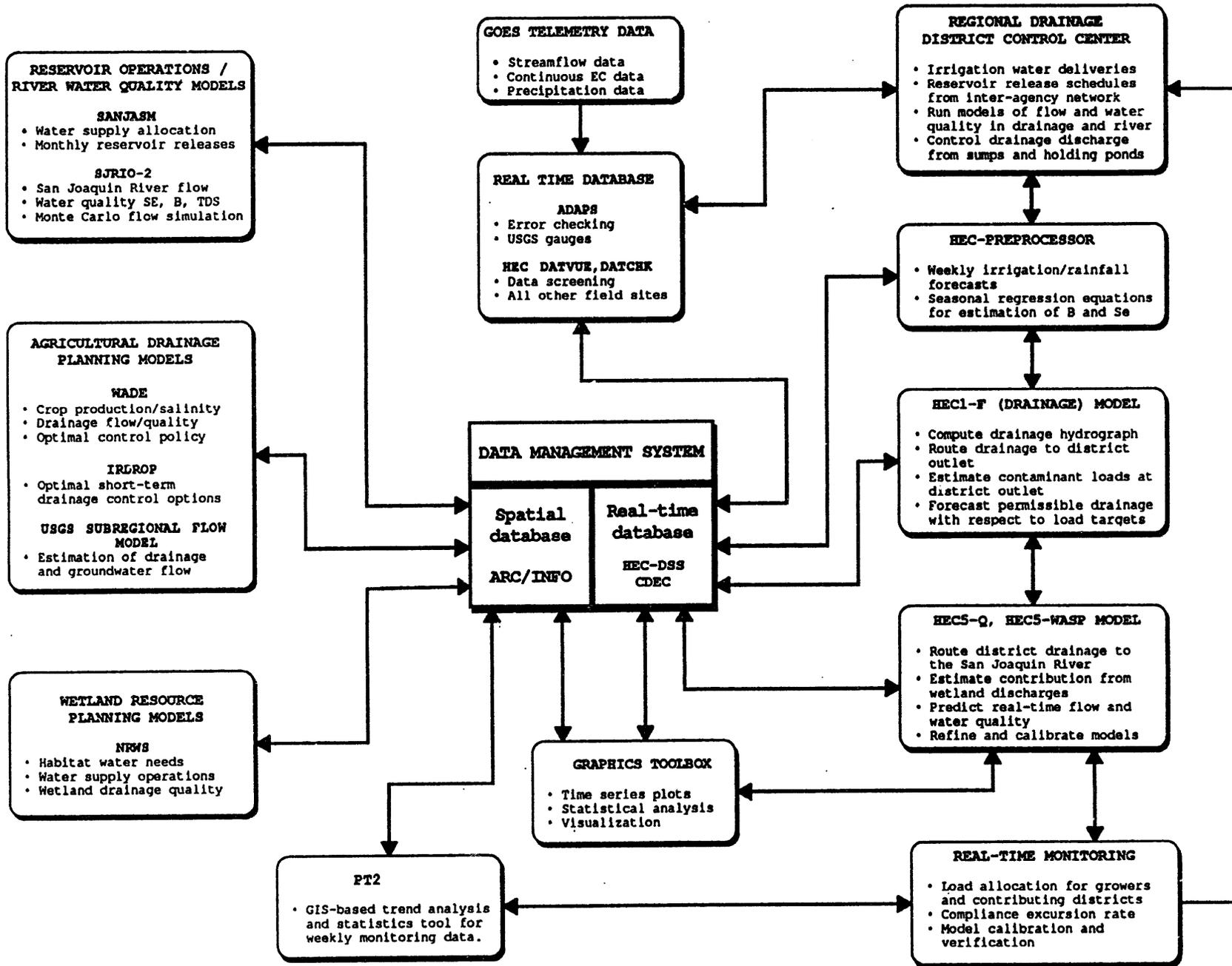


Figure 2. Drainage Management Support System for the Grasslands Basin

criteria for selenium, boron and TDS. The model accepts tributary inflow to the San Joaquin River produced by SANJASM. Surface returns and diversions to/from the main stem of the San Joaquin River at 0.8 km intervals, are provided to the SJRIO-2 model as an input data file. Mud and Salt Sloughs are the major discharge points for contaminated agricultural drainage to the River as well as the major outlets for pond drainage from seasonal wetlands and wildlife refuges in the Grasslands Basin. Approximately 85% of the selenium load, 70% of the boron load and 50% of the TDS load at the monitoring site immediately below the confluence with the Merced River is contributed by Mud and Salt Sloughs. Ground water flow to the 100 km main stem of the San Joaquin River is calculated every 1.6 km using a simple Darcy flow model. The SJRIO-2 model performs monthly flow and water quality mass balances for TDS, selenium and boron at more than 180 locations along the San Joaquin River.

The **Natural Resources Workstation (NRWS)** is a GIS-based decision support system, developed at Colorado State University (Garcia, 1992), that provides graphical user interfaces to a HEC5-based, wetland supply and drainage model and the SJRIO-2 model (Figure 3). The networks of the wetland supply and drainage model and the SJRIO-2 model share common nodes allowing the output from the former to be passed on to SJRIO-2. The GIS contains spatial habitat data for the various State and Federal wetlands in the Grasslands Basin and program modules allow the calculation of water supply requirements and drainage water quality at the time of seasonal wetland releases. Rules for filling of wetlands and scheduling of releases are currently being formulated within HEC5.

The **Westside Agricultural Drainage Economics Model (WADE)** was developed by the San Joaquin Valley Drainage Program and CH2M-Hill to simulate regional agricultural drainage flow and water quality under various regional drainage reduction and source control policies. The model comprises three interacting sub-models (a) an agricultural production sub-model which simulates cropping decisions, farm revenue, irrigation and drainage technology selection and activity levels of drainage recycling, ground water pumping and irrigation recharge; (b) hydrology and (c) salinity sub-models which simulate water tables, root zone and aquifer salinization, and drainage volume and quality. The sub-models solve sequentially for a winter pre-irrigation period and a summer irrigation period for each year simulated. The agricultural production

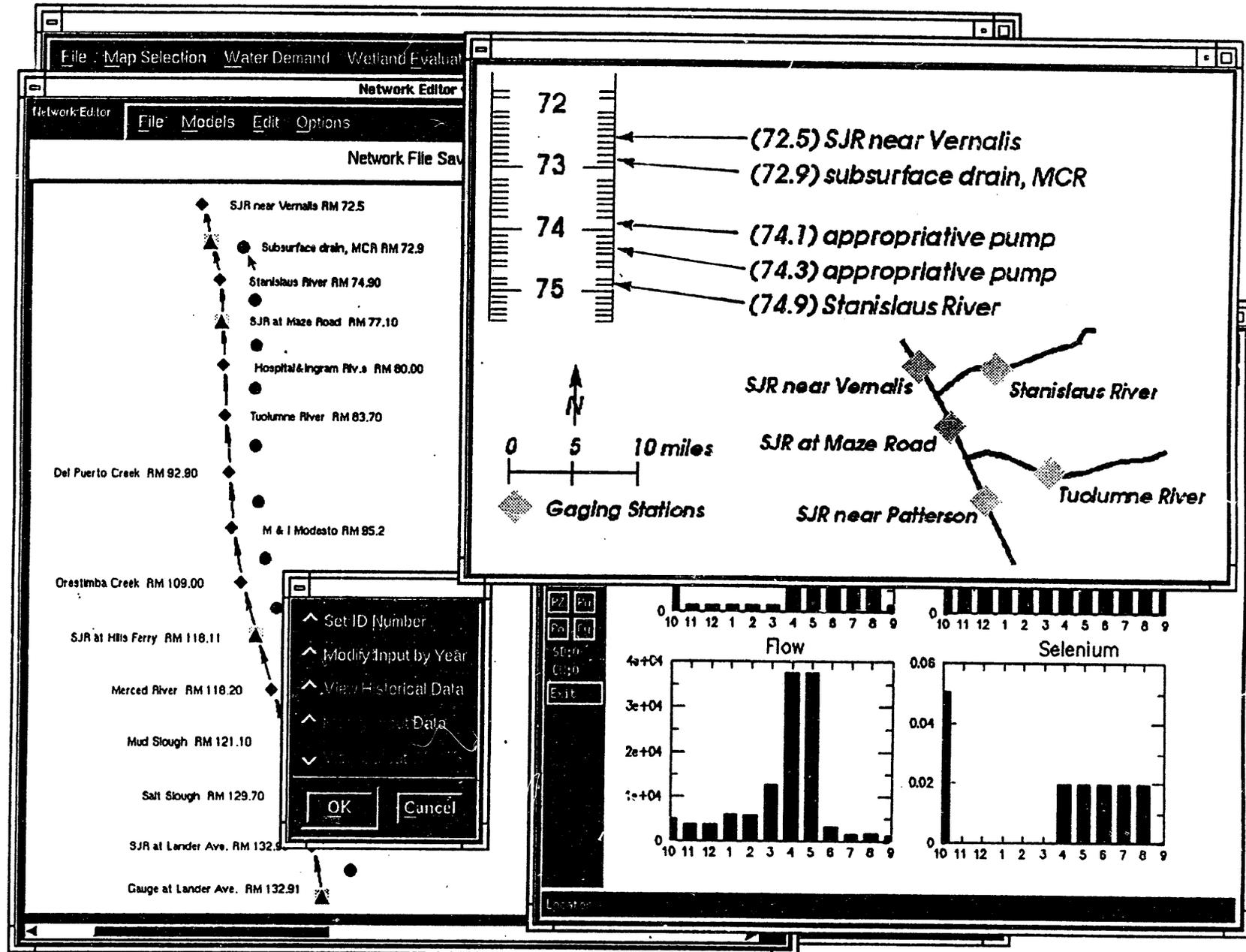


Figure 3. Graphical user interface for the SJRIO-2 model within the Natural Resources Workstation. By selecting the circular symbol adjacent to each network node, a detailed diagram of surface water inflows and diversions for each reach is provided, as shown. Histogram plots of monthly San Joaquin River flow and contaminant concentrations for the real-time monitoring station at Vernalis is shown beneath the detailed reach diagram.

sub-model is formulated as a linear optimization model - hence the sub-model attempts to prescribe the actions the growers should perform to maximize net returns to investments in land and labor, in response to a variety of economic constraints or water district policies. The model can also be constrained to adhere to water quality objectives set in terms of annual allowable loadings of TDS.

The **Irrigation and Drainage Operations Model (IRDROP)**, developed by CH2M-Hill (USBR,1991) selects optimal monthly drainage management strategies for agricultural drainage discharges constrained by SWRCB water quality objectives for selenium and boron and the assimilative capacity of the San Joaquin River for these contaminants. Strategies simulated by the model include: (i) recycling of subsurface drainage (several water districts have facilities which allow separation of surface and subsurface drainage return flows and allow blending with fresh water supplies); (ii) conjunctive use pumping of ground water (to control seasonally high water tables and reduce the volume of subsurface drainage requiring disposal); (iii) drainage storage in holding ponds (mostly during those months when the total drainage discharge cannot be accommodated by the San Joaquin River without exceeding water quality objectives); and (iv) use of available irrigation supply water to dilute drainage discharges to comply with SWRCB water quality objectives. The model utilizes WADE model algorithms to simulate interactions between irrigation practices, water use, drainage flow, water quality and soil salinity.

A **USGS sub-regional (MODFLOW) flow model** (Fio,1993) of the southern Grasslands Basin will be used to obtain initial estimates of water table elevations and subsurface drainage flows, under a number of future water conservation and drainage reduction policy scenarios. The model will be valuable in the refinement of water balances in the IRDROP model and in estimating river accretions in the SJRIO-2 model. The sub-regional flow model will also have value in developing drainage flow hydrographs in the HEC1-F flow forecasting model, described in Section 4.

4. Operations models for real-time analysis, drainage forecasting and control

Moving from screening and feasibility studies of workable source control and drainage management strategies to real-time management of drainage and continuous compliance with water quality objectives requires a more

sophisticated decision support system. This system must be capable of generating short term forecasts of drainage flow, drainage contaminant loads and river assimilative capacity for selenium and boron. Opportunities exist to better coordinate the timing of reservoir releases, agricultural drainage discharges and wetland releases to take advantage of periods when the San Joaquin River has assimilative capacity for salt and trace element loads and reduce or eliminate discharges to avoid violations of water quality objectives when assimilative capacity is exceeded. Provision of short-term forecasts of San Joaquin River flow and water quality conditions would also assist downstream farmers, in the Sacramento-San Joaquin River Delta, to schedule irrigation operations to avoid periods when River salinity is highest. Development of a real-time, decision support system will require the processing of real time flow and water quality data from monitoring stations along the San Joaquin River and its tributaries. Agricultural drainage systems will require retrofitting, in some cases, to allow improved control over drainage discharges. Technologies such as in-line, adjustable weirs, closely-spaced, shallow tile drains installed on the contour, drainage sumps and sump pumps have been shown to improve water table and management of drainage discharges and, in the future, may accommodate automation. Real-time flow and water quality stations will also be needed in the wetland areas of the Grasslands Basin to monitor wetland discharges to the San Joaquin River during the winter and early spring, and relay this information to the Regional Drainage District and other interested parties.

The challenges in developing a system for real-time management of river water quality and drainage discharge in the San Joaquin Basin are many. Building a real-time decision support system for drainage management from scratch would be a formidable task. However, existing tools, such as the real-time water control system, developed by the Hydrologic Engineering Center of the Army Corps of Engineers, can be adapted to simulate subsurface drainage through a pipe network. The HEC software is extensively used in the eastern and central United States for rainfall-runoff estimation, flood forecasting and flood control operations planning. The HEC water control software system is data centered and comprises a suite of interactive computer programs that access real-time data, view and perform error checks on the data, produce

rainfall and runoff forecasts based on antecedent data, and simulate the effect of upstream reservoir releases at downstream gauges.

A schematic of a real-time decision support system for drainage management, showing the adapted modules from the HEC water control system is shown on the right side of Figure 2. The same data-centered approach using the HEC Data Storage System (DSS) is illustrated in the diagram. The California Data Exchange (CDEC) is the current repository of real-time flow and water quality data from telemetered monitoring sites along the San Joaquin River and would be linked to download raw data directly to the DSS.

Raw telemetry data, obtained either from CDEC or the GOES satellite, would be processed using the HEC modules DATVUE (for reviewing and editing the data) and DATCHK (which screens the data for errors and missing values according to pre-set flags and rate of change conditions). This software could be run routinely at the offices of a Regional Drainage District which would act as a control center for making irrigation water deliveries, obtaining weekly reservoir release schedules, managing drainage water releases, monitoring compliance with San Joaquin River water quality objectives and providing information to regulators, farmers and downstream irrigators. At the present time, the legal and institutional procedures for creating a regional drainage district are being studied by the water districts in the Grasslands Basin receiving CVP water supply.

Once the real-time data have been processed, checked and missing values estimated, a pre-processing program would be used to convert continuous electrical conductivity (EC) data to estimates of selenium and boron concentrations, based on year-type and season-based regression equations. Weekly irrigation schedules for each drainage catchment within the Grasslands Basin would be added to forecast precipitation in this system module.

The HEC-1F program would be adapted to compute agricultural drainage hydrographs from subsurface drainage catchments. These subsurface drainage catchments will be delineated according to the detailed tile drainage maps, residing in the GIS. Calibration of the catchment routing parameters will follow the same protocol used for surface water catchments. Additional code would be written for HEC-1F to permit drainage load hydrographs to be generated from the agricultural drainage flow hydrographs. The flow routing equations used in HEC-1F will be used to estimate the transit times from each

drainage catchment to the point of discharge into the San Joaquin River. HEC-1F would be used to make weekly forecasts of drainage flow and drainage water quality generated by agricultural water districts and discharged to the San Joaquin in the absence of Regional Drainage District intervention.

The NRWS version of HEC5, which includes the EPA water quality model WASP, can be used to route agricultural drainage discharges to the San Joaquin River to each of the water quality compliance points on the San Joaquin River at Newman, below the Merced River (selenium and boron) and at Vernalis (EC). The HEC5-WASP model could also be used to simulate wetland releases, which increase salt loading to the San Joaquin River in the late winter and spring. A weekly optimization model, based on IRDROP, would be developed to choose between the most effective drainage control strategies if the forecasting and routing models suggest that water quality objectives will be violated without some intervention. Another function of the Regional Drainage District would be the continuous calibration and refinement of the decision support system models. The District would also be in a position to recommend changes to the real-time monitoring system to improve model forecasting ability.

Figure 2 also shows a link to the GIS-based trend analysis and data visualization package, PT2. This software package allows interrogation of objects, representing all water quality and biota monitoring locations within the Grasslands Basin. The monitoring locations contained within PT2 include internal stations within the Grasslands Basin that are not directly relevant to calibration of the drainage forecasting decision support system but can provide vital information on water quality trends.

5. Discussion

The major shift in water allocation policy in California, brought about by passage of the CVPIA, serves to emphasize the need for integrated, system-wide management of limited water resources to meet urban, agricultural, wildlife and environmental needs. An inadequate support system of integrated simulation models and forecasting tools exist to help water resources professionals screen and manage innovative drainage management strategies. This paper has described an interagency initiative to develop a real-time monitoring and drainage management system. This system could allow the scheduling of drainage discharges and reservoir releases to provide the greatest mutual benefits to

agriculture, fisheries and power producers without violating water quality objectives. It may also allow downstream irrigation diversions to be scheduled to occur at times when the San Joaquin River water quality is highest by those accessing the real-time monitoring system. For this system to be developed, implemented and used, many obstacles will need to be overcome. These obstacles are technical, financial and institutional and will require the close cooperation and good faith of many individuals, water districts, public agencies and regulators. This undertaking may be a forewarning to water resources planners in other countries, where irrigated agriculture is a major consumer of developed water supplies and where competition for limited water resources is intense. As science continues to gain new insights into the environmental consequences of irrigated agriculture - we must become ever more creative and vigilant at water management and continue to develop techniques that enhance our ability to make wise decisions.

6. Acknowledgements

The authors wish to thank Dr George Moridis, Lawrence Berkeley Laboratory, Mr Art Tuma, U.S. Bureau of Reclamation and Mr Joe Karkoski, California Regional Water Quality Control Board for their review and helpful comments. The first author also wishes to convey his gratitude to the U.S. Bureau of Reclamation, in general, and Mr Michael Delamore, Chief of the Water and Power Resources Division, in particular, for their support of his interest in real-time drainage management in the San Joaquin Valley. The work described in this paper was supported by the U.S. Bureau of Reclamation under the U.S. Department of the Interior Interagency Agreement No. 0-AA-20-09410, through U.S. Department of Energy Contract No. DE-AC03-76SF00098.

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