A Decision Support System for Real-Time Management of Water Quality in the San Joaquin River, California

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Abstract: The paper describes a real-time decision support system for monitoring and minimizing exceedences of water quality standards in the San Joachim River Basin, California, USA. The river system supports extensive irrigated agriculture, and there are many stakeowners in its boundaries with often competing interests. Results are presented of particularly interesting case events. Future improvements are suggested.

1. INTRODUCTION

The San Joaquin River (SJR) drains the San Joaquin Valley and affects flow and water quality in the San Francisco Bay Delta. Its many uses have resulted in a significant degrading of water quality, fish and wildlife habitat, flood protection capacity and recreation opportunities. In 1990, the California legislature authorized the establishment of the San Joaquin River Management Program to identify the problems facing the river system and prepare a plan that would identify solutions to improve, restore and enhance currently degraded conditions. As part of this program, a water quality subcommittee was formed to identify the river's major water quality problems and to work towards the implementation of solutions. Members of the SJRMP Water Quality Subcommittee include representatives of the California Department of Water Resources, Lawrence Berkeley National Laboratory, United States Bureau of Reclamation and California Regional Water Quality Control Board. The SJRMP-WQS identified salinity,

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selenium and boron as being the most important water quality parameters in the SJR system. Subcommittee members recognized that improved management and coordination of tributary releases and agricultural and wetland drainage flows could improve compliance with State water quality objectives at key monitoring locations along the SJR. To implement this action plan, subcommittee members identified the need to provide information on current and forecasted flow and water quality conditions to SJR water managers.

2. BACKGROUND

The impetus for real-time water quality management in the San Joaquin Basin is to decrease the frequency with which water quality standards are exceeded along the main stem of the San Joaquin River. The San Joaquin River is considered to be one of the most highly regulated rivers in the world.

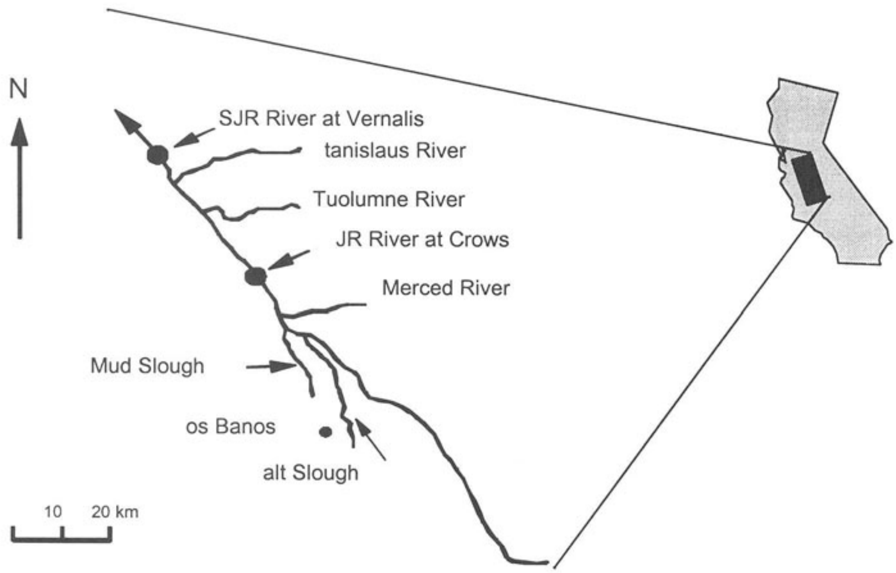

Figure 1. Major tributaries to the San Joaquin River between Lander Ave and Vernalis.

The San Joaquin River basin is formed by the crest of the Sierra Nevada on the east, the Coast Range on the west and is bounded by the Kings River itself on the south. Eight major rivers and 15 minor streams feed the SJR, which runs over 350 miles (563 kilometers) from its origin in the Sierra Nevada. These major tributaries to the SJR drain an area of about 15,000 square miles (38,850 square km). For over 200 miles (322 km), from Friant Dam to the Delta, the river flows west to a shallow reservoir named Mendota Pool, then continues north to join with the Merced, then Tuolumne and Stanislaus rivers, then finally west again into the Delta.

Most of the natural flow impounded behind Friant Dam, on the upper San Joaquin River, is diverted north and south for agricultural irrigation. Consequently, over 20 miles (32 km) of river channel upstream from Mendota Pool is dry in most years. The Delta-Mendota Canal, built about the same time as Friant Dam, conveys Delta water to Mendota Pool to supply irrigation water to farmlands in the lower SJR basin. A portion of the applied water returns to the river as surface or subsurface drainage further increasing the river's salt content. During dry years, the largest component of the flow in the lower SJR comprises agricultural drainage. The SJR basin contains a series of reservoirs that gather and store snowmelt later used for hydropower generation and water supply. Of the 57 major reservoirs in the basin, four can store up to 1,000,000 acre-feet (1,233 million m^3) or more each, another 12 can each store up to 100,000 af (123 million m^3). Fifteen reservoirs were built primarily for flood control; however, many of them also store water. Reservoir releases provide storage for flood flows, satisfy agricultural irrigation water demands, support a river rafting industry and provide pulse flows to aid migrating chinook salmon. Adult chinook salmon return to the tributaries to spawn beginning in October and the resulting salmon smolts leave the tributaries and pass through the Delta to the Pacific Ocean during the spring.

Occasionally, large discharges of high quality water from east side tributaries are followed by large discharges of poor quality water from west side sources. These poor quality discharges - such as subsurface agricultural drainage and wetland releases conveyed by Mud and Salt sloughs - often cause SJR water quality objectives to be exceeded. Impounded waters in seasonal wetlands and wildlife refuges are released according schedules that optimize conditions for waterfowl habitat. Agricultural drainage discharges are highest during the irrigation season, peaking during the pre-irrigation season after crop germination. In the recent past, reservoir releases, agricultural drainage discharges and wetland releases have been made independently without attention to water quality in the SJR, although the US Bureau of Reclamation has a legal obligation to meet Vernalis water quality objectives through releases from New Melones Reservoir on the Stanislaus

River resulting from a court setllement reached between the agency and a water district in the South Delta.

Water quality objectives (Table 1) have been set for selenium and boron at Crows Landing (immediately downstream from the confluence with the Merced River) and for salinity at Vernalis (below the confluence with the Stanislaus River) . The assimilative capacity for each of these contaminants is defined as the contaminant load (in kg or tonnes) that the river can still accept before exceeding the contaminant objective for compliance. Positive assimilative capacity means more of the contaminant can be discharged into the river without exceeding objectives. Negative assimilative capacity quantifies the load of the contaminant that must be removed to meet objectives.

Water Quality Constituent	Irrigation Season (April to September)	Non-irrigation Season (October to March)
Electrical Conductivity (EC)	700 uS/cm	1,000 uS/cm
Total Dissolved Solids (TDS)	420 mg/l	600 mg/l
Boron	1 mg/l	1 mg/l
Selenium	5 ug/l	5 ug/l

Table 1. Vernalis Water Quality Objectives (SWRCB, 1987)

3. CONCEPTUAL REAL-TIME WATER QUALITY MANAGEMENT

Real time water quality management is composed of four main activities: data collection, data processing, data analysis, and data dissemination. Raw data must be quickly assembled and checked for accuracy prior to data analyses. To be effective as a management tool, these activities must be executed in real time and the data analysis component must consider the impact of disseminating results to coordinate water management activities in the basin.

Typically, river stakeholders manage water according to a set of rules that dictate when water is stored, used, or discharged. These stakeholders operate independently, making decisions on water use that are based on the quantity and or quality of water supplies available to them and their own individual needs. Individuals with a specific interest in a basin, such as reservoir operators, manage a reservoir based on a set of criteria that includes flood control, water delivery, power generation, and recreation demands. Each criteria is further controlled by a combination of long term or seasonal specifications such as seasonal maximum storage allowances, as well as short-term specifications such as rainfall or reservoir inflow.

Real time water quality management in the SJR basin relies on a collaborative approach that encourages and facilitates SJRMP participants, under their existing authority, to voluntarily reduce water quality impacts on one another. The SJR real time water quality monitoring network is expected to improve average water quality and dampen existing wide water quality fluctuations now experienced over short periods at water quality compliance points such as Vernalis. Successful implementation assumes that if all these interests can be informed of one another's actions, they will adjust their operational schedule to minimize conflicts. If conflicts continue in spite of reliable information on the adverse effects, a regulatory approach could be called for by interests whose uses are harmed. Benefits of real time water quality monitoring and management in the SJR basin include increased coordination of releases and diversions that can avert much of the high salinity and trace element levels and/or the effects on beneficial uses. With better information on upstream conditions, downstream users can adjust their timing of use to avoid diverting irrigation water with high salt or high boron concentrations. Reservoir releases can be timed to improve flows for fish migration and agricultural uses. Releases of saline water may be matched to the assimilative capacity of the SJR to help reduce the concentration of salts in the basin. Finally, releases of saline water from wetlands and drainage systems can been scheduled to coincide with the need for outflows sought by fisheries managers.

4. SAN JOAQUIN RIVER WATER QUALITY FORECASTING MODEL

Real time water quality analyses are currently made using an existing monthly model, the San Joaquin River Input-Output model (SJRIO), utilizing hydrologic routing techniques and conservative mass transport to calculate water quality. The model performs a mass balance accounting of discharge, TDS, boron, and selenium for a 60-mile (96-km) reach of the lower SJR, bounded by the gaging stations at Lander Avenue in the south to Vernalis in the north (Figure 1). The SJR at Lander Avenue was chosen as the upstream boundary for the model for three reasons: (1) it is downstream of the effects of the east side bypass on SJR flows, (2) it is upstream of wetland discharges and agricultural drainage inputs from Mud and Salt sloughs, and (3) historical data exist with which to validate the model. The SJR near Vernalis was chosen as the downstream boundary because it is upstream of Delta tidal effects and it has long-term historical data to calibrate the model (Kratzer et al. 1987). The SJRIO study area is depicted in Figure 2, along with the locations of significant stream flow and water quality gaging stations.

SJRIO2 was modified to run on a daily time step so that it could be used with real time flow and water quality data on the SJR. This daily version of the model, SJRIODAY, uses the same basic inputs and outputs as SJRIO. The model calculates the load contributed from each source based on its flow and concentration using a mass balance accounting method. SJR flows and water quality are calculated for every tenth of a mile (161 m). Model inputs for which there are no available real time data are estimated using mean monthly data. Monthly data for the current month is typically not available for most other model components. Instead, similar year mean monthly data must be used as described below.

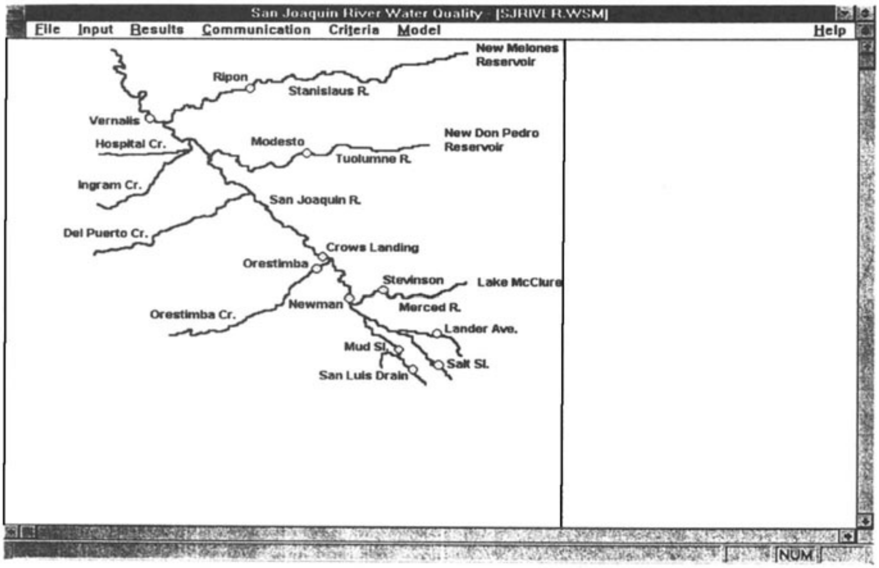

Figure 2. Monitoring sites on the San Joaquin River and the major tributaries.

Seventy-five diversion pumps on the SJR and the east side tributaries were identified from a review of water rights files and field surveys (Kratzer et al. 1987). Riparian diversions are estimated using three types of data: acreage irrigated by each pump, cropping patterns, and crop water use. Irrigated acreage and cropping patterns are assumed to remain mostly unchanged; although cropping patterns for individual fields may vary, there tend to be no large scale changes from year to year. The acreage and cropping patterns associated with each diverter are assumed constant. Flow and water quality data are few for the nine subsurface discharge points into the river.

Annual flows from tile drains were estimated by multiplying tile drainage factors ranging from 0.65 to 0.85 acre-feet per acre (1,980 m^3 per hectare) per year by the tile drained acreage. Annual tile drainage was multiplied by the monthly distribution of flow to get an average monthly tile drainage at each site. Average monthly TDS, boron, and selenium concentrations were determined based on a survey of available data for sumps and drains in the area (Kratzer et al. 1987).

Gauged surface agricultural return flow data are available for the east side from two major water districts: Modesto Irrigation District and Turlock Irrigation District. West side surface return flows are assumed to be about thirty percent of the supplied irrigation water (Kratzer et al. 1987). Water is supplied from three sources: diversions from the SJR, groundwater pumping, and Central Valley Project water. Pumped groundwater for water years 1961 to 1977 are based on consumptive use of water and power consumption records, reported by the USGS in 1983. SJRIO2 uses the average of each of four water year types - critically dry, dry, normal, and wet.

Three wastewater treatment plants discharge to the SJR: Newman, Turlock and Modesto. All plants record discharge volumes and salinity (e.g., TDS or EC). Limited boron data are available, so boron values are kept at constant monthly values. Selenium concentrations are assumed to be zero as supported by CRWQCB studies (1988a) that found selenium discharges from these sources to be less than 1 part per billion. Groundwater accretions or depletions and quality are considered steady state and are defined by the modeler in the file GW.DAT for user-specified reaches of the river.

Monthly evapotranspiration from the banks of the SJR is based on acreage of riparian vegetation and average monthly potential evaporation for grass. A survey of riparian vegetation (Katibah et al. 1980) was used to estimate the amount of riparian vegetation for each five mile (8 km) segment of the SJR. Evaporation from Class 'A' pans in Fresno (DWR, 1976b - 1990b) were multiplied by a factor of 0.92 to obtain a rate appropriate for evaporation from the SJR (Kratzer et al. 1987). A volume for net evaporation was then calculated using average SJR surface areas.

5. DECISION SUPPORT SYSTEM

To develop a functional decision support system the SJRMP-WQS developed software to retrieve pertinent data from the field sensors, allow quality assurance checks to be performed on the downloaded data, fill data gaps, display data graphically, then transform the data into information useful to operational decisions. The most important innovation was the development of the Windows™ - based, graphical user interface (GUI) which was simple to use and served the needs of modelers and stakeholder's alike.

The purpose of the GUI is to assist stakeholders who make operational decisions on drainage discharges, recycling and temporary storage with respect to the assimilative capacity of the SJR. The GUI, facilitates the inspection of real time and forecast data, and features Internet communication capabilities that expedite the collection of certain model input and dissemination of water quality forecasts. The GUI consolidates modeling activities to one responsible party to eliminate confusion resulting from water managers viewing model results created from different input data. An Internet FTP site on a local area network stores files exclusively pertaining to GUI operation. The "visual" desktop image generated by GUI software allows the user to operate a computer by using a mouse or other pointing device to manipulate icons or menu options that represent application software, files containing data, and/or operating system commands.

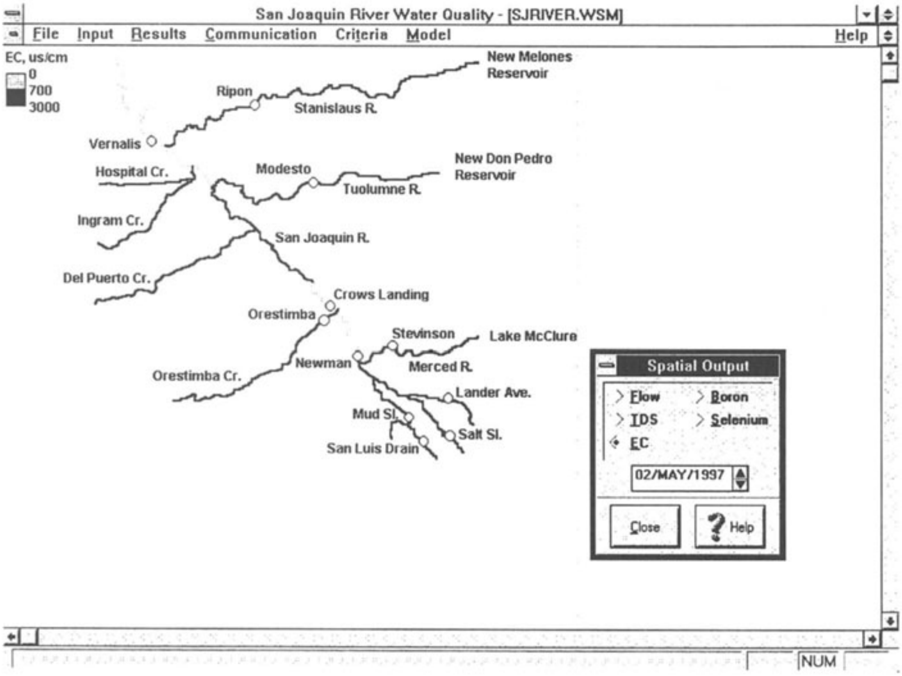

Figure 3. GUI screen showing color coded reaches of the San Joaquin River that are above the Vernalis monthly objective for salinity (EC).

The easy-to-use features of the GUI include the point-and-click system of Windows™, on screen data entry, map-based outputs, and Internet-based communication. The GUI main screen is depicted in Figure 3. The horizontal menu bar that appears on top of the map includes items File, clicking at a menu item will lead to a pull down menu for additional choices. Key input and output sites (e.g. Vernalis) are located on a graphic of the SJR system. Pointing then clicking at such sites lead to a graphic that compares model results versus preliminary real time data.

Upon executing the GUI a map of the San Joaquin River system is displayed on the computer screen. Nodes depicting major tributaries, diversions and compliance points are represented as red dots on the display. According to the Windows convention, a horizontal menu bar is provided for the pull-down menus. The user can direct the arrow cursor to any part of the map on the computer screen, and, using the point and click system, recall the data for review or for changes of input conditions. Pointing and clicking on the any of the red dots allows the user to view either observed or simulated flow information at that site or obtain concentrations or mass load information for selenium, boron or total dissolved solids.

Within the communication menu are routines to upload operational schedules or to download model results. Reservoir operators can enter daily schedules of diversions and discharges and upload these schedules every two weeks to the person making the flow and water quality forecasts. Likewise, this person can also use the GUI to download operational schedules from agencies where timely data is routinely posted to a public ftp site. The criteria menu may be selected to specify the color code used to display the spatial variations of water quality. These criteria selected are used in the calculation of the assimilative capacity. Results from model runs can be viewed as a time series or by spatial location. When time series is chosen, a dialog box appears for the selection of flow, TDS, boron, or selenium. By clicking consecutively on TDS, flow and a location on the map, the flow and TDS concentrations are graphed for a three week period. If spatial is chosen, a dialog box prompts the user to choose between flow, TDS, boron or selenium for display. The color representation of water quality is usually set according to the water quality objective. In the case of salinity, the concentration objective for the non-irrigation season is 618 mg/l (1000 uS/cm EC). When the EC in the river is above the threshold value of 618 mg/l, the river segment will be colored red. Below the threshold concentration, the river is colored green (Figure 3).

Another feature of the GUI is the ability to view the river's assimilative capacity at various selected locations. The Assimilative Capacity is selected on the Time Series menu instead of Concentration. The values for assimilative capacity are calculated on the basis of what the user entered for threshold criteria (e.g., 420 mg/l for TDS). Figure 4 is the assimilative capacity at Vernalis for the SJRIODAY run beginning 5/5/97.

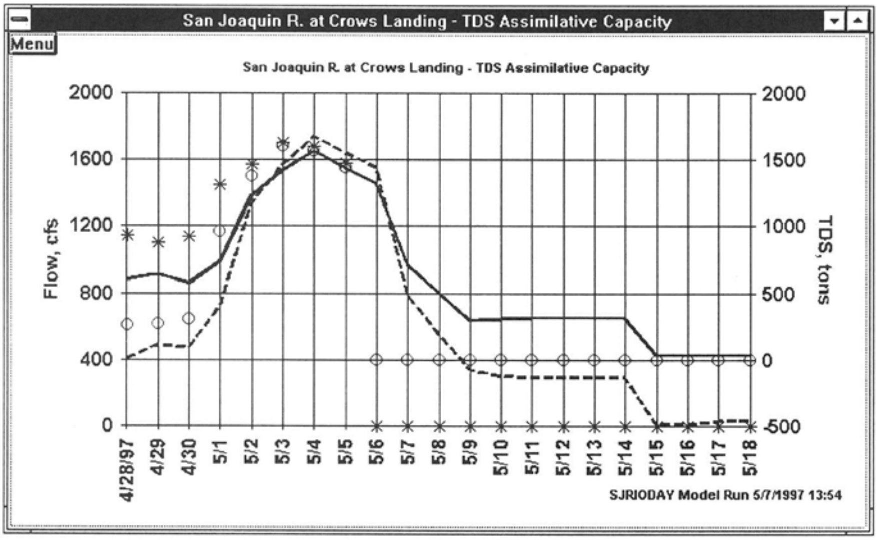

Figure 4 Assimilative capacity at Vernalis for the SJRIODAY run beginning 5/5/97

The user can scroll through a display of dates, viewing the temporal variations of water quality parameters at any map location on the screen and can display spatial color coded changes in water quality at any given time. By clicking at a time advance button, the user can create a near-animation of how a slug of poor quality water moves through San Joaquin River.

The GUI allows water managers to coordinate their operational decisions on a weekly basis by providing a spreadsheet-type entry of operational schedules consisting of the past week's operation and two weeks projected operation. Water managers can then upload their operational schedule to the FTP site for use by SJRMP-WQS modelers, who then incorporate the information into model run input data. Water managers can download model run results from the FTP site, display the results and review the run-specific comments. Water managers who decide to change his/her operational schedule as a result of the model run output can contact SJRMP-WQS members by telephone or email. The model run input data are revised accordingly, then SJRMP-WQS staff runs the model again and posts the revised run results of the FTP site.

SJRMP-WQS members maintain contact with interested parties by holding regular subcommittee meetings and posting the highlights of these meetings on a listserver (sjrwqop@sacto.mp.usbr.gov). Other information posted on the bulletin board, besides SJRMP-WQS meeting minutes and SJRIODAY model run results, include announcements of other meetings related to SJR water quality, changes in Stanislaus River release schedules by the USBR and other operators. SJRMP-WQS members have given several presentations and workshops on SJR real time water quality monitoring and management to interested parties, including staff and executive management from State, federal and local agencies, environmental groups, engineering consultants, and attorneys representing east-side tributary operators.

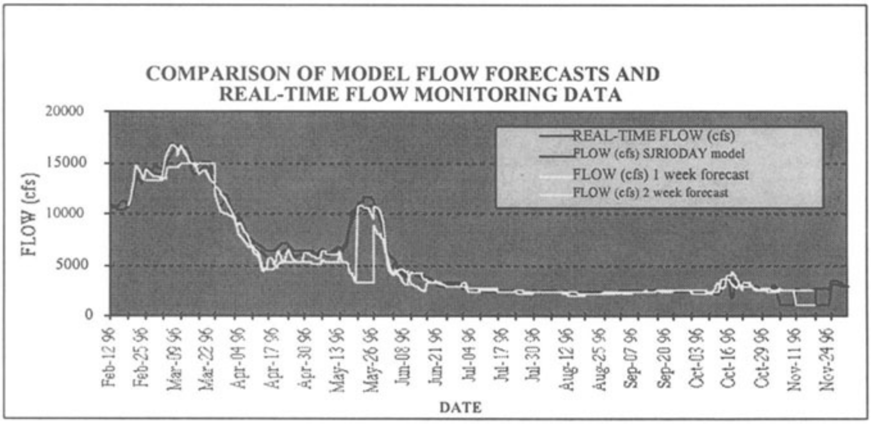

Figure 5. Model Flow Forecast Compared to Real-Time Data

Two types of documentation files are available by selecting Model from the main menu, then Info. The user can view a text file describing the forecasting model or view information pertaining to the most recently downloaded run. Help from the main menu provides explanations and/or descriptions of various GUI commands, menus, features and the like.

6. IMPLEMENTATION

A Memorandum of Understanding that expresses the commitment of the undersigned parties to the operation, maintenance and expansion of the San Joaquin River Real-Time Water Quality Network was circulated among water agencies, water districts and other interested parties. MOU signatories receive a free copy of the GUI software, and with it, the capability of obtaining real time forecasts.

7. MODEL RESULTS AND FORECASTS

Forecasts of flow and water quality at Vernalis have been made each week since November 1995 and a post audit of forecast accuracy has been broadcast on the electronic listserver, comparing the forecasts with observations obtained from the real-time monitoring system. Figures 5 and 6 show the performance of the forecasting model for predicting flow and TDS at Vernalis. The observed and model simulated flows at Vernalis and the observed and simulated TDS concentrations and assimilative capacities are in closer agreement in the case of the 1 week forecast than for the 2 week forecast, as might be expected. The model performed well during most of 1996 and, in particular, the summer months, when flows and water quality on the San Joaquin River were dominated by agricultural drainage from Mud and Salt Sloughs (Figure 5). In general, the model tends to overestimate flow as well as EC. Between December 25, 1996 and January 25, 1997 the San Joaquin Valley was subjected to severe winter storms which produced an extraordinary volume of runoff from the east-side Sierran watersheds. Figure 5 illustrates the problems encountered in making accurate flow forecasts during this period. Without an accurate watershed model runoff forecasts were based on estimates of the flood hydrograph from each contributing watershed and real- time flow data.

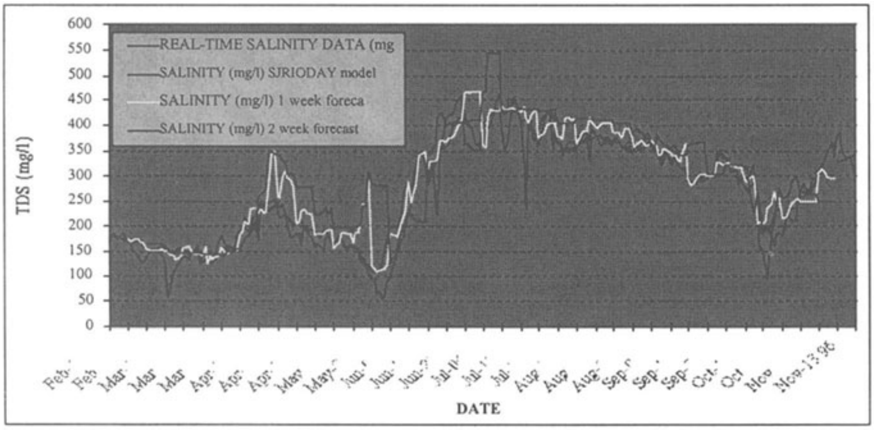

Figure 6. Model salinity forecasts compared to real time salinity data.

Although both model and forecast flows continued to overestimate real-time flows between January 14 and January 25, 1997 levee breaks along the San Joaquin River diverted considerable flood flow and may account for much of the error. The dominance of east-side tributary flows on San Joaquin River water quality during this period made the EC somewhat easier to predict with accuracy. Model and forecast EC are not significantly different from the real time EC data (Figure 6).

8. CASE STUDY

During early January 1996 the Grassland Water District, a water district that supplies water to approximately 40,000 ha of private wetlands and duck clubs, sought to make an early drainage release of ponded water to reduce the likelihood of downstream salinity impacts and salinity objective violations in the San Joaquin River later in the season. The Water District requested that the SJRMP-WQS provide a forecast of the most advantageous time to make this release. A model forecast, made on January 15, 1996 suggested that the combination of high river flows and an imminent rainstorm might provide the necessary assimilative capacity. The peak wetland release was timed so that it would coincide with the peak flow in the San Joaquin River. Wetland flushing began on January 18 and ended on February 19, with the peak flow occurring between January 27 and February 10. This peak flow arrived at Vernalis between February 1 and February 14. On January 15, before the arrival of the wetland releases, flow at Vernalis was approximately 2000 cfs (56 m^3/s) and the EC was 1000 uS/cm. At the time of arrival of the peak wetland releases at Vernalis, flow at Vernalis ranged from 5,300 to 10,500 cfs (150 to 295 m^3/s and the EC ranged from 220 to 430 uS/cm. Assimilative capacity was positive in the River throughout the simulation period owing to the rainfall-runoff events in the upper watershed. No violations of the EC objective occurred during the trial period and there were no EC violations in the San Joaquin River during March and April, 1996.

9. FUTURE WORK

The installation of additional continuous flow and water quality monitoring stations within both agricultural water districts and wetland areas within the Grasslands Basin could help to improve the accuracy of San Joaquin River water quality forecasts. A greater challenge will be gaining cooperation of the east-side reservoir operators, wetland water managers and agricultural water districts to manipulate their release schedules. Each institution has its own operating rules that are followed to satisfy the needs of their clients and customers. There are few incentives or requirements for these institutions to assist in water quality management of the San Joaquin River at the present time. Policy changes and financial incentives may be needed to foster cooperation from these institutions.

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