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Model integration for assessing future hydroclimate impacts on water resources, agricultural production and environmental quality in the San Joaquin Basin, California

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Abstract

The US National Assessment of the Potential Consequences of Climate Variability and Change provides compelling arguments for action and adaptive measures to help mitigate water resource, agricultural production and environmental quality impacts of future climate change. National resource planning at this scale can benefit by the development of integrated impact analysis toolboxes that allow linkage and integration of hydroclimate models, surface and groundwater hydrologic models, economic and environmental impact models and techniques for social impact assessment. Simulation models used in an assessment of climate change impacts on water resources, agriculture and environmental quality in the San Joaquin Basin of California are described in this paper as well as the challenges faced in linking the component models within an impacts assessment toolbox. Results from simulations performed with several of the tools in the impacts assessment toolbox are presented and discussed. After initially attempting model integration with the public domain, GIS-based modeling framework Modular Modeling System/Object User Interface (MMS/OUI), frustration with the framework's lack of flexibility to handle monthly timestep models prompted development of a common geodatabase to allow linkage of model input and output for the linked simulation models. A GIS-based data browser was also developed that works with both network flow models and makes calls to a model post-processor that shows model output for each selected node in each model network. This data and output browser system is flexible and can readily accommodate future changes in the model network configuration and in the model database.
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1. Introduction

In the past decade concerns about possible global climate change and its impacts on water resources and agricultural production have stimulated interdisciplinary research in climatology and water resource systems engineering. Water resource management agencies have been challenged as a result of this research to formulate policy and local strategies to cope with the contingency of climate change. In the arid San Joaquin Valley of California, a four billion-dollar agricultural economy is dependent on irrigation for its viability. Changes in the reliability of water for irrigation in this Basin as a result of future climatic change could have serious consequences for the California economy. Contingency planning will require the development and linkage of analytical tools and simulation models for resource management under climate change. This paper describes an integrated modeling toolbox developed to evaluate water supply, agricultural production, environmental and social impacts to climate change in the San Joaquin River Basin (SJRB).

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1.1. Background

The SJRB contains two million hectares of cropland, receives an average of 200 mm of precipitation annually and hence relies on both local and imported irrigation water supply to meet the needs of agriculture. The east side of the SJRB is supplied by four tributaries, the Stanislaus, Tuolumne, Merced and Upper San Joaquin Rivers that originate in the Sierra Nevada mountain range and provide high quality snowmelt water during spring months (Fig. 1). During dry and critically dry years flow in the SJR is dominated by agricultural drainage flows from the west side of the Basin. West-side subsurface agricultural drainage and surface drainage from managed wetlands contain high concentrations of soluble salts and trace elements such as boron and selenium. In spite of constraints imposed on agricultural, wetland and municipal return flows to the SJR, the contaminant loading from these sources remains the single most important determinant of the ecological health of the Bay–Delta ecosystem, which supplies drinking water to 20 million people.

2. Climate change studies

A number of California climate change studies have been conducted that assumed doubled atmospheric carbon-dioxide and applied both general circulation models (GCMs) and hydrologic models (Lettenmaier and Ghan, 1990; Dracup and Pelmulder, 1993) to simulate impacts. The GCMs considered were the models of the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute for Space Studies (GISS), and the Oregon State University Department of Meteorology (OSU). The three GCMs are described by Manabe (1969), Hansen et al. (1983) and Schlesinger (1984), respectively. The large-scale planetary signals from the GCMs generated weather patterns that provided data to hydrologic models to estimate mean monthly streamflow in the SJR and its major tributaries.

Conclusions drawn from these studies agreed that a global warming trend in California would likely lead to more severe winter storms, earlier runoff from the Sierra snowpack, and reduced summertime flow in tributary streams. Reduced volumes of summertime flow produce less stored water in State and Federal reservoirs leading to shortages to water contractors, especially those located south of the Sacramento-San Joaquin Delta. This situation is a result of the uneven distribution of water resources within the State where the majority of the mountain snowpack and the developed water supply is located in the north-western part of the State and is conveyed south through the State's elaborate distribution system.

Most of these studies focused on streamflow response to shifts in the timing and form of precipitation and did not address the issue of inter-annual variability or scaling issues inherent in mapping GCM output to the more detailed watershed hydrologic models. In addition, they did little more than make qualitative statements about the implications for these changes for the environment in the SJRB, in particular about agricultural, water quality, fishery or socioeconomic impacts. The modeling toolbox

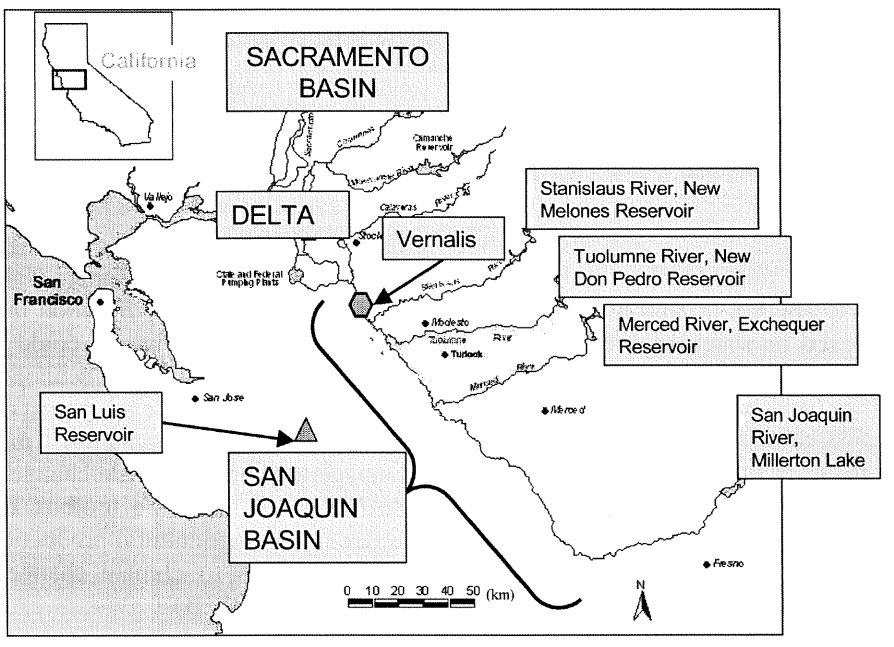

Fig. 1. Map of the San Joaquin River Basin (SJRB) showing major east-side tributaries and the water quality compliance monitoring station at Vernalis.

developed in the present study addresses these deficiencies.

2.1. Weather and climate simulations

Weather and climate simulations for the current study were performed by downscaling large-scale data derived from GCMs to nested limited area models (Miller and Kim, 1997). Fig. 2 illustrates the sequence of climate, weather and hydrology models used in this analysis. Output products include regional hydroclimate simulations (monthly precipitation, snow budget, soil moisture, streamflow, temperature, wind, surface energy and water budgets) for short-term forecasts, seasonal-scale experimental predictions, and long-term climate scenarios (Miller et al., in press). A pre-processor prepares data from GCMs, global analysis, land surface geographical information, satellite and other remotely-sensed information to help automate the downscaling procedures.

In the present study, four climate simulations were performed based on the published results from two competing GCMs—the Hadley Centre Model (HadCM) (Johns et al., 1997), which produces results for California that show relatively wet and warm climatic trends, and the National Center for Atmospheric Research Pacific Climate Model (PCM), which produces relatively cool and dry projections. These models are considered to represent the two end members of large number competing GCMs. For each climate simulation, two scenarios were produced representing present-day climate (PC) and an annual transient increased changed climate. The methodology followed for simulating climate uses two climate change (CC) projection members from separate ensemble projections (HadCM and PCM), each representing a transient one-percent annual increase in average global greenhouse gas (GHG) concentrations (Miller et al., submitted for publication). The study focused on two 30-year periods (2010–2039, 2050–2079) and one 20-year period (2080–2099), regarding them as future climatological periods centered about 2025, 2065, and 2090, respectively. This resulted in six CC scenarios being developed: HadCM2025, HadCM2065, HadCM2090, PCM2025, PCM2065, and PCM2090. For each scenario, California's modified hydrological conditions were represented using rainfall-runoff simulations in five representative watersheds, which drain into Sacramento and San Joaquin River Basins. To improve the accuracy of the snowmelt and runoff forecasts, the downscaled data was organized by tributary basin. The Merced River Basin and the Kings River Basin in the SJRB were chosen as representative of the hydrology of the east-side tributaries of the SJR (Miller et al., submitted for publication). The Kings River Basin, located in the southern Sierra Nevada along the south edge of the SJRB, is hydraulically connected to the SJR during high flow conditions when some of its flow is diverted north; otherwise the Kings River flows south into the Tulare Lake Basin. The Merced River Basin lies at a higher altitude basin than the Stanislaus, Tuolumne and San Joaquin Basins and therefore accumulates more precipitation as snowfall than the adjacent Basins. It also requires larger temperature shifts to initiate snowmelt. Hence, the Kings River Basin was used to represent the upper Stanislaus, Tuolumne and SJR Basins.

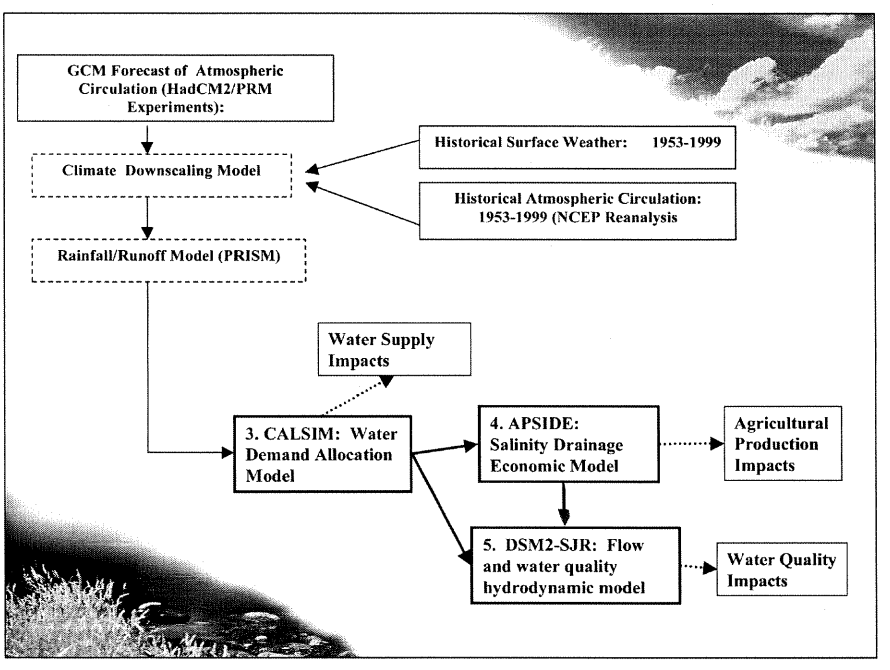

Fig. 2. Sequential linkage of models to (a) generate climate change hydrology from existing HadCM2 and PRM Global Circulation Model (GCM) outputs and (b) simulate impacts of climate change on SJRB water resources, agricultural productivity and water quality.

Streamflow for each basin was simulated using an application of the National Weather Service—River Forecast System Sacramento Soil Moisture Accounting Model (Burnash et al., 1973) coupled to the snow accumulation and ablation Anderson Snow Model (Anderson, 1973). Basin models were validated using streamflow and mean upper-basin and lower-basin area precipitation and temperature data (i.e. mean area precipitation, MAP and mean area temperature, MAT, data) archived by the National Weather Service from 1953 to 1999, a period representative of the present climate (PC) hydroclimatology in the Miller et al. (submitted for publication) study (i.e. MAP_{PC} and MAT_{PC}).

MAP and MAT data for each CC scenario, rainfall-runoff simulation were developed from the GCM data using historically derived regression equations based on the PRISM technique (i.e. the Parameter elevation Regressions on Independent Slopes Model (Daly et al., 1994)), where GCM temperature and precipitation data were first downscaled to 10-km spatial resolution, then aggregated into MAP_{CC} and MAT_{CC} data, and finally both temperature and precipitation data were averaged within each calendar month yielding 12 climatological values for each projection period. Daily MAT_{CC} and MAP_{CC} data for each basin and each scenario were then created by first measuring MAT_{PC} and MAP_{PC} sensitivity to climate change for each calendar month. These monthly factors were applied to the historic daily temperature and precipitation data; climate series temperature sensitivities were expressed as the mean monthly incremental difference between MAT_{CC} and MAT_{PC} to produce daily MAT_{CC} data for simulation; precipitation sensitivities were expressed as the ratios of MAP_{CC} to MAP_{PC} to create daily MAP_{CC} data for simulation (Miller et al., submitted for publication).

Streamflow responses to climate change, derived from Sacramento model simulations, were represented in the form of climatological monthly streamflow perturbation factors (Table 1). These factors represent a monthly percent change in CC relative to PC streamflow and were used in this assessment as a basis for creating reservoir inflow perturbation factors for reservoirs in the State Water Project (SWP) and Federal Central Valley Project (CVP). These streamflow perturbation factors were applied to a 74-year historic time series of monthly reservoir inflows to create the climate change scenarios. Some of the factor values are high for winter months in the HadCM scenario (e.g., Merced, Kings) because HadCM results indicate a shift in the annual runoff pattern where proportionately more runoff occurs in winter relative to spring. Historically, winter runoff has been quite small in these basins because annual runoff has been dominated by spring–summer snowmelt.

Table 1
Streamflow perturbation factors, expressed as percentage of the monthly inflow into each terminal reservoir, for the stationary 1970–1994 historic time period at a year 2000 level of development

HadCM streamflow ratios	2010–2039	2050–2079	2080–2099
October–March	~2	~2	~5
April–September	~0.8	~0.8	~0.5
PCM streamflow ratios	2010–2039	2050–2079	2080–2099
October–March	~1	~1	~1
April–September	~0.5	~0.5	<0.5

3. Water resource simulation models

In order to simulate the impacts of potential changes in hydroclimatology on water resources, agricultural economic sustainability and environmental quality, a series of water agency-supported simulation models were employed. These models were each developed independently and as a consequence are difficult to use for interdisciplinary studies that move beyond the limited range of cause–effect relationships that each of the individual models was designed to simulate. Information is processed sequentially through these models; rainfall runoff predictions from the climate models are transformed by a set of rules and system constraints to arrive at agency water allocation decision; these water allocations impact agricultural production in the watershed which in turn affects the quantity and quality of agricultural subsurface drainage; agricultural drainage combines with tributary flows in the SJR to modify instream water quality; instream water quality can have impacts on fishery and wildlife resources. Because these models are independent, they have redundancies—that is there are certain decision variables that are estimated independently by more than one model. An example of this redundancy is the calculation of SJR electrical conductivity (EC) at the Vernalis compliance monitoring station, which is made according to a regression equation by the water allocation model CALSIM-II (http://modeling.water.ca.gov/hydro/model/index.html), and by mass balance using the hydrodynamic river model DSM2-SJR (http://modeling.water.ca.gov/delta/models/dsm2/index.html). Feedback loops between models are necessary to resolve these discrepancies and to avoid mass balance and accounting errors in the simulation.

3.1. Water allocation and streamflow simulation (CALSIM-II)

CALSIM-II is a hybrid linear optimization model which translates the unimpaired (i.e. natural) streamflows into impaired streamflows, taking into account reservoir operating rules and contract water demands exerted at model nodes, modified to reflect a year 2001 level of watershed development. The model code is written in a high-level programming language called WRESL (http://modeling.water.ca.gov/hydro/model/

WreslLanguageReference.pdf), developed by the California Department of Water Resources (DWR) (2002), and the system of WRESL equations is solved using a proprietary solver XA (Sunset Software Inc.). CALSIM-II was developed jointly by the State DWR and Federal US Bureau of Reclamation (USBR) to represent the joint Federal (CVP)–State (SWP) water supply delivery system. The model is used to simulate existing and potential water allocation and reservoir operating policies and constraints that balance water use among competing interests. The model assumes static monthly water requirements for a wide variety of agricultural crops which are not affected by CALSIM-II, includes existing contract water delivery goals for Federal, State and other users of California's developed water supply and imposes constraints (weights or penalty functions) on water allocation based on existing regulations for managing SJR water quality, Delta water quality, and SJRB anadromous fish migration. The model output includes monthly reservoir releases, channel flows, reservoir storage volumes, and parameters describing SJR and Delta water quality conditions.

In a typical CALSIM-II model run, output from the regional climate simulation models provides input unimpaired streamflow data, which are processed to provide monthly flow volumes within the major east-side and west-side watersheds, that collectively drain into the SJR (Fig. 2). Calibration of the model involves tuning the objective function weights to ensure adherence to water supply operations rules and instream flow and water quality constraints. The model has distinct advantages over previous "hard-coded" Fortran models in that it allows policy and operating rule adjustments to be made with relative ease and in an explicit, easily identifiable manner. This is of particular benefit for contingency planning under future climate change scenarios where additional storage or changes in flood storage and release policies may be explored as ways of improving the reliability of water supply under forecasts of increased future demand. It is also the reason this model was selected as part of the climate change impacts assessment toolbox.

The 74-year time series of reservoir inflow data, used by CALSIM-II, represents historically observed inflow from 1922 to 1995 and is intended to represent the hydroclimatology of the present climate. The state and federal agencies typically determine year-type classifications early in the year to set up water allocation priorities for the remainder of the year. This allows contractors subject to shortages to have sufficient time to explore alternative water supply options, such as water markets and groundwater pumping. CALSIM-II simulates water allocation using nine independent hydrologic year-type classification systems. Each one is designed for a particular CVP, SWP, or Delta water resource management objective, and has two to six year-type categories ranging from very critical (dry) to wet. Monthly climate change reservoir inflows were calculated by simply multiplying the reservoir's monthly present climate inflows with the monthly perturbation factors of that reservoir's headwater basin or an associated basin. The historic 74-year reservoir inflow time series was necessarily reclassified for the CC scenario, the year-type classification affects the values used to constrain water demand, water quality, groundwater pumping, and minimum instream flow requirements. Simulations of water supply deliveries were made using CALSIM-II for both the HadCM2 and PCM GCM downscaled hydrology.

3.2. Agricultural production and drainage salinity (APSIDE)

To address issues pertaining to agricultural production response to changes in long-term water allocation, a unique Agricultural Production Salinity Irrigation Drainage Economics model (APSIDE) has been developed (Quinn et al., 2001). APSIDE is a non-linear mathematical programming model written in the GAMS (Generalized Algebraic Modeling System) language and uses the non-linear solver CONOPT2 to obtain monthly optimal solutions to the model objective function (GAMS Development Corporation, 1998). The objective function maximizes agricultural production and on-farm revenue subject to environmental and policy constraints affecting subsurface drainage to the SJR. Subsurface drainage flows from agricultural lands on the west side of the SJRB, because of the marine origin of the soils, have a significant impact on SJR water quality. This optimization approach has been used with considerable success for the past decade by the California Department of Water Resources to simulate agricultural production on salinity and selenium-affected lands in the San Joaquin Basin subject to drainage contaminant load constraints (Howitt, 1995; Howitt and Lee, 1996). The APSIDE model receives as input the annual water deliveries predicted by the CALSIM-II model to determine crop production, groundwater pumpage and irrigation return flows for individual water districts within the San Joaquin Basin (Fig. 2). The model currently simulates agricultural yield and productivity response to reductions in water supply, irrigation water quality, root zone and groundwater salinity and to predict future agricultural drainage flows and water quality (Quinn et al., 2001; Hatchett, 2001). Sensitivity analysis has demonstrated the primacy of drainage disposal costs, groundwater pumping costs and the individual crop yield response to salinity in determining future farm income. The APSIDE model also simulates flow and salinity mass fluxes between the crop root zone, the shallow semi-confined aquifer, deep semi-confined aquifer and confined aquifer in order to continuous update the root zone salt balance as well as take account of the migration of more saline

groundwater from the shallow semi-confined aquifer to the deep aquifers as a result of pumping drawdown.

3.3. River flow and water quality simulation

Monthly drainage return flows simulated by the APSIDE model must be routed to the SJR in order to determine the impact of these activities on SJR water quality. The one-dimensional hydrodynamic flow and salinity model, DSM2, was extended to include the SJR (henceforth referred to as DSM2-SJR) and was used to simulate the transport of salts from the point of discharge to Vernalis. The hydrodynamic module of DSM2-SJR (HYDRO) calculates flow in the SJR using river cross-section data and estimated bed roughness along each reach. The flow model takes account of inflows to and withdrawals from the SJR as well as the processes of direct seepage and evaporation. The water quality module (QUAL) is based on the USEPA QUAL2E model (http://www.cpa.gov/QUAL2E—WINDOWS/) and accounts for salt load along each reach of the SJR. SJR flows and water quality are calculated every 160 m (10th of a mile). Riparian diversions are currently estimated using three types of data: acreage irrigated by each pump, cropping patterns, and crop water use. Groundwater accretions or depletions and quality are currently considered steady state and are defined by the modeler for user-specified reaches of the river.

The flow and water quality computation performed by DSM2-SJR is superior to the flow-salinity static regression equation, used in CALSIM-II, to estimate salinity concentration at Vernalis and to simulate required reservoir released from New Melones Reservoir to meet Vernalis electrical conductivity (EC) objectives. One of the primary authorized uses of New Melones storage is for the maintenance of a 30-day running EC objective at Vernalis. Hence in instances where the 30-day running average salinity objective is exceeded, CALSIM-II Stanislaus River dilution flows need to be updated, as does the storage volume in New Melones Reservoir. This requires iteration of the CALSIM-II model during dry and critically dry years when the flow dominance of the east-side tributaries is diminished and west-side salt discharge to the SJR, upstream of the Stanislaus River, exceeds the river assimilative capacity.

3.4. Results of model simulations

To illustrate the utility of the impact assessment toolbox developed in this project results are presented for water allocation and salinity management under climate change (Brekke et al., submitted for publication). CALSIM II model simulation results are shown for three multi-year drought periods experienced in California for the years 1928–1934, 1976–1977, and 1986–1991. Drought periods are instructive in that they produce the greatest stresses on the water conveyance and water allocation infrastructure of the State and expose deficiencies in water supply reliability. These drought events are simulated using a 2001 level of development. Level of development refers to the dams, irrigation canals, groundwater pumping stations, river diversion structures, etc. that exist and are functional in the State at any point in time. One way to assess the impacts on SJRB west-side deliveries is to consider the ratios of water delivery relative to water supply demand for all CVP agricultural users south of the Delta. The CALSIM II model attempts to maximize contract deliveries to all State and Federal contractors each year using available developed water supply and subject to system, legal and environmental constraints. In this study, this ratio is used as an index of water shortage in the SJRB and as an indicator of stress in the water supply infrastructure.

3.5. CALSIM-II water allocation impacts under HadCM

Under a HadCM-based climate change, reservoir inflows increase dramatically, impacting the ability of the State and Federal reservoir system (at the 2001 level of development) to store wet-season flood flows. Under this climate change scenario, the SJRB east side inflow from the Sierra Nevada mountains accounts for 25% of annual SWP and CVP inflow using 2001 data. For the 2025 period, the greatest impacts would occur during winter and spring months (i.e. December–May), with an 80% increase relative to 2001; the annual inflow increase would be 57%. By 2065 these percentages rise to 127% and 85%; and, by 2090 they increase to 236% and 152%. The HadCM-based results differ from the conclusions drawn by previous studies whereby climate change will result in warmer winter storms, less snowpack accumulation, and lower spring–summer streamflow and water supply (e.g., Revelle and Waggoner, 1983; Dracup and Pelmulder, 1993). Rather, the HadCM-based results suggest that CVP–SWP aggregate inflow and SJRB inflow during spring–summer would remain largely unchanged through 2065 with reductions appearing at 2090 (Fig. 3). Moreover, these 2090 spring–summer reductions would be more than offset by increased winter and early-spring inflow, which might allow for maintained spring–summer water deliveries. The reason for the inconsistency between previous studies' results and those presented, is that previous studies did not consider a climate scenario as wet as the HadCM projection.

Given significantly increased inflow under the HadCM scenarios, instream flows and reservoir release volumes would increase and water allocation goals would be more easily achieved, given the abundant water supply. The greatest opportunity for increasing SJRB reservoir storage occurs during relative years (e.g., New Melones Reservoir). Noticeable increases were

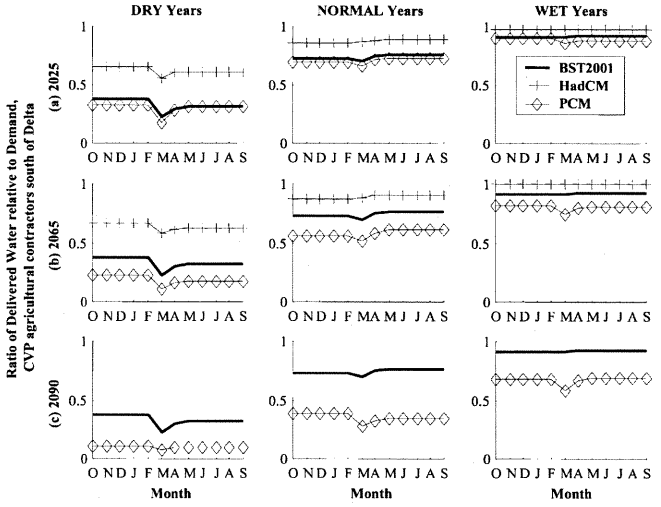

Fig. 3. Simulated mean-monthly delivery level (as a percentage of demand) among CVP agricultural users south of the Delta (including the SJRB): (a) 2025, (b) 2065, and (c) 2090.

simulated for 2025 and became more pronounced by 2065. In relative dry years, simulated CC-based reservoir release volumes changed little because existing reservoir storage capacities allowed for more stored water assuming 2001 conditions. In contrast, reservoir release volumes during relative wet years increased significantly during the winter months because the 2001 residual storage capacity is small compared to the anticipated wet year inflow volumes under HadCM climate change. Looking at HadCM-based impacts, water quality conditions at the SJR Vernalis compliance monitoring station experienced little effect relative to 2001 conditions.

3.6. CALSIM-II water allocation impacts under PCM

In contrast to HadCM-based assessment for reservoir inflow impacts, PCM-based results of water delivery relative to demand (Fig. 3) are consistent with conclusions made in previous studies. Climate change that results in warmer winter storms, less snowpack accumulation, and less spring/summer reservoir inflow (e.g., Lettenmaier and Ghan, 1990; USBR, 1991; Miller et al., 1999) leads to lower delivery/demand ratios.

Impacts to SJRB inflow illustrate the spatial signature of potential climate change impacts on California hydrology (Miller et al., submitted for publication). For the 2025 period, virtually no impact is expected in the SJRB with spring–summer inflow decreasing by less than 1% and annual inflow *increasing* by 1%. By 2065, these percentages, decrease by 23% and 13% for the spring–summer and annual period, respectively. By 2090 the spring–summer and annual percent decreases become 44% and 24%, respectively. Under PCM climate change, decreases in project reservoir inflow would increase competition among system users, thereby increasing the significance of water allocation priorities on distributing the deliveries impacts throughout the system. Using New Melones Reservoir as an example of SJRB east side stored water and release impacts both conditions would remain largely unchanged by 2025. However by 2065, the effects of reduced reservoir inflows would induce stored water volume decreases for all water-year types and corresponding release volume decreases, especially during wet years because the reduced dry and normal year stored water conditions would require less wet year releases to mitigate the increased susceptibility to multi-year drought events. This impact is most pronounced by 2090 when wet year release volumes are reduced year-round.

Given the decreases in reservoir inflow and stored water volumes, SJRB aggregate deliveries would suffer. The SJRB east side would experience virtually no change in delivery volume as late as 2065. Not until 2090 are the volume decreases, relative to 2001 conditions, very significant, and then only during relatively dry years. By contrast, the west-side delivery reductions are significant in 2065 for relative dry years and in 2090 for both relative dry and normal years.

Evaluating the ratios of PCM-based delivery relative to demand for all CVP agricultural users south of the Delta, the suggested impacts would be small by 2025. The 2001 demand delivery ratios were estimated to be 33%, 74%, and 92% of average demand for dry, normal, and wet years, respectively. By 2025, the deficits under PCM climate change worsen relative to 2001, as the ratios become 30%, 71%, and 89%; by 2065, they are 19%, 58%, and 80%; and, by 2090, they have diminished to 10%, 35%, and 67%. With decreased reservoir inflow, decreased stored water, high prioritization of water allocation for water quality management relative to agricultural production, consumptive deliveries would be expected to bear the brunt of water shortages created under PCM climate change.

Reduced reservoir inflow, stored water conditions, and water supply available for all uses under PCM climate change would intuitively lead to more constraints on managing salinity conditions at the SJR Vernalis compliance monitoring station (Fig. 4). However, given CALSIM-II's flexibility to make allocation adjustments within the system, results show that adverse impacts at Vernalis would not be expected until 2065, and only for the most severe simulated drought event (i.e. the 2065-perturbed "1928–1934" event) where a sharp increase in summer salinity conditions occurs near the end of the multi-year event. The 2090-perturbed "1928–1934" event presents a greater challenge as salinity spikes occur by simulation year 1930 (Fig. 4); a salinity spike also occurs near the end of the "1986–1991" event.

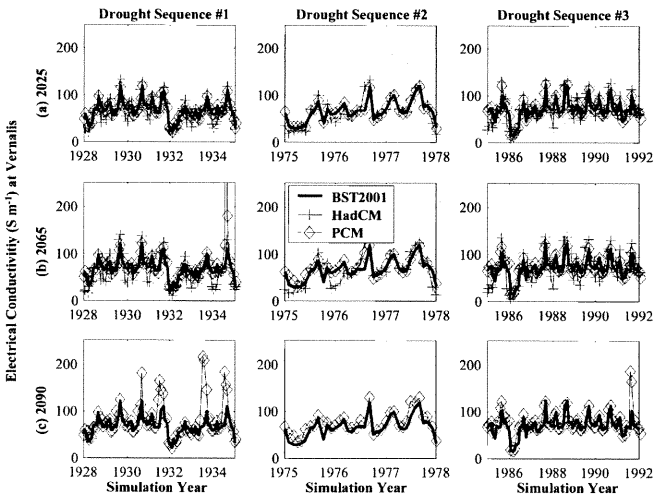

Fig. 4. Simulated electrical conductivity ($\mu S\ m^{-1}$) at Vernalis during historically significant drought events: (a) 2025, (b) 2065, and (c) 2090.

3.7. APSIDE agricultural production impacts under PCM

Output from the APSIDE model is shown in Fig. 5. Only the PCM output is reported since APSIDE is not expected to deviate from the base condition under the surplus water supply conditions produced by the wet HadCM scenarios. For the 2025 PCM climate scenario, the linked downscaling, rainfall runoff, basin hydrology and CALSIM-II models produce a reduction in mean monthly precipitation and a decline in reservoir storage. These impacts suggest an average annual reduction in water deliveries of about 50% to west-side federal water districts such as the Broadview Water District for normal to dry years (50% obtained by averaging dry and normal year results) on the west side of the SJRB. Although these reductions in deliveries do not produce a significant change in drainage return flows from the water districts in the simulation—water quality shows a significant response at the end of a 20-year simulation, leading to an increase in drainage salt concentration during summer months (Fig. 5), as farmers pump more groundwater and recirculate more of their drainage water. This increase is typically matched by an increase in residual salinity within the crop root zone. Drainage volumes predicted by the APSIDE model are dynamic, since they are the result of potential changes in agricultural land use, irrigation and drainage technology adoption and land retirement decisions over time. The static return flow estimates calculated by CALSIM-II must therefore be updated with these newly calculated estimates. Calibration of the basin scale APSIDE model that updates the estimates of west-side drainage flow and salt loads is the subject of ongoing research.

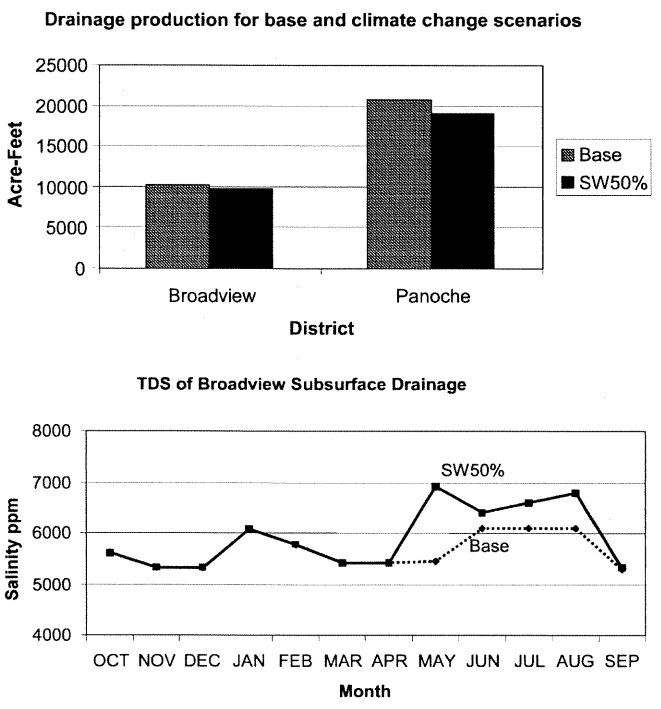

Fig. 5. Effect of a 50% reduction in available water supply in subsurface drainage salinity from typical water districts within the Grasslands sub-basin on the west side of the San Joaquin Valley. Graphs illustrate a reduction in summer drainage with reduced water delivery and an increase in long-term drainage water quality in summer months due to increased groundwater pumping and drainage recycling.

3.8. DSM2-SJR flow and water quality under PCM

As previously described, the regression relationship, developed to relate flow and Vernalis electrical conductivity in the CALSIM-II model breaks down under a PCM climate change scenario, where responses to water shortages in the Basin result in greater groundwater pumping and subsurface drainage recycling (Fig. 6). Basin level drainage flow and salt load estimates, obtained from APSIDE, are provided as input to DSM2-SJR, to obtain a more accurate estimate of Vernalis water quality. CALSIM-II is rerun iteratively with the new estimate of Vernalis EC, which will in turn change releases from reservoir storage to meet the water quality objective. A closure criterion must be set to limit the number of model iterations.

4. Model integration

One of the difficulties in linking mathematical models that were not designed to work together is resolving data inconsistencies and making provision for model feedback where one model such as DSM2-SJR is capable of producing a superior estimate of an important state variable, such as Vernalis EC. It is this aspect of model integration that is the most tedious and which works against the principles of modularity and object oriented

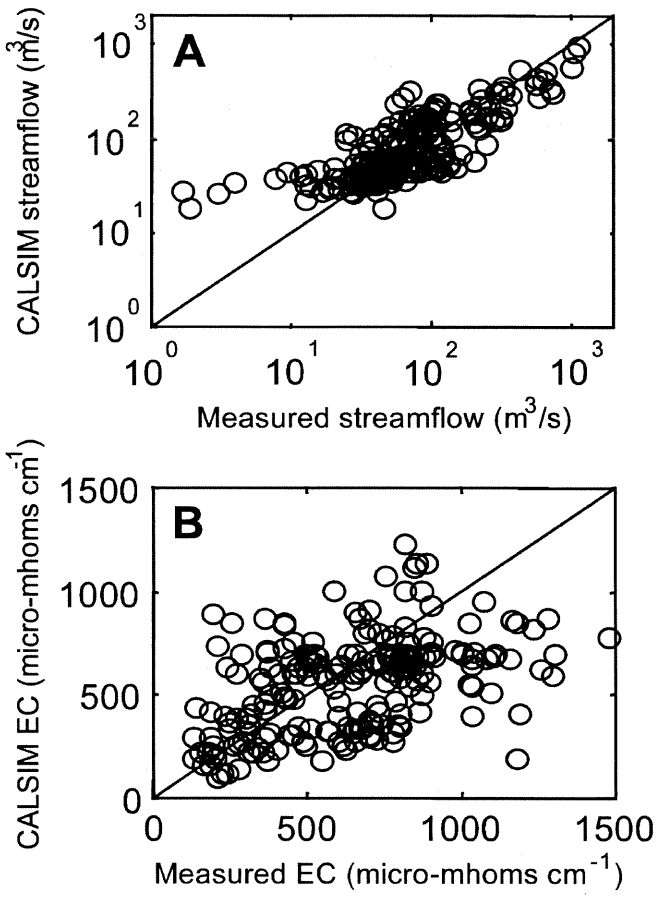

Fig. 6. Comparison between measurements and CALSIM II estimates of (a) streamflow and (b) electrical conductivity at Vernalis. The diagonal line represents the 1:1 slope (perfect agreement), values above (under) this line were over (under) estimated by CALSIM II. Historical data from 1973 to 1995.

model construction and use. Model integration was considered of highest priority for the models, CALSIM-II, APSIDE and DSM2-SJR. These models collectively contain hundreds of decision variables many of which will need to be revised based on applicable policy and level of development assumptions. The first step in integration was to design a common database format that the models could each read from and write to. It was fortuitous that the authors of both the DSM2-SJR and CALSIM codes chose the Hydrologic Engineering Center's Data Storage System (HEC-DSS) as their database of choice. HEC-DSS is a non-relational, efficient database for time series data, is in the public domain and has been used for two decades as the data engine for a suite of HEC water resource models. The Generalized Algebraic Modeling System (GAMS) data structures for the APSIDE model have been translated through the use of simple Java–Python scripts to HEC-DSS file format. The second step was to georeference all three models within a common Geographical Information System (GIS). The CALSIM-II model nodes were not spatially defined, hence it was impossible to resolve the stream gains, losses and diversions between network nodes for the two models. Since the level of disaggregration in DSM-SJR is much greater than CALSIM-II, this has required GIS mapping of basin catchments and comparing stream reach gains, losses and return flow estimates with independent estimates from a groundwater-surface water model for the San Joaquin Basin. A map-based, graphical user interface (GUI) was conceived that allowed the data to be retrieved through interrogation of the base map and using graphical output displayed at each element/node for each model.

5. Data integration architecture

The Modular Modeling System/Object User Interface (MMS/OUI) (Leavesley et al., 1996) was initially selected as a framework for model integration. The OUI modeling framework contains pre-processing, model run, post-processing and visualization libraries that allow individual models or modules of an existing model to be "shrink wrapped" and hence treated as objects within a GIS-based Decision Support System. The model component includes tools written in Java and C programming languages to selectively link process modules to perform the variety of simulation tasks called for within the Decision Support System and delegated to each model. The GIS layers for each model were successfully loaded into the OUI; however, problems were encountered in developing the Java code for the data management interface (DMI) between HEC-DSS and OUI. The MMS/OUI developers have recently produced a DMI for HEC-DSS but only for models operating on a daily timestep. All the models in our system operate on a monthly timestep. Consultation with the code developers revealed that the reprogramming required to allow a monthly timestep option was non-trivial—our team did not include a programmer capable of working with the source code, nor was this part of the scope of our EPA-funded project. MMS/OUI was therefore rejected for our application. Should a variable model timestep feature be added in the future the integration system would be reconsidered since it has many powerful GIS-based modeling attributes that are ideally suited for a study such as the one described in this paper.

A more generic approach to integration and visualization of data was conceived using new features available in the Environmental Research Systems Institute's (ESRIs) Common Object Module (COM) based architecture. A collaborative development effort was initiated involving the California Department of Water Resources (DWR) and the Bureau of Reclamation Mid-Pacific Region to develop an ArcObjects-based GIS interface for the CALSIM II, DSM-2 and APSIDE models. A primary motivating factor for this effort was to georeference each of the models to allow construction of a geo-

database. The nodal networks for the CALSIM-II or DSM2-SJR models were previously only partially tied to geographical features—in most cases only at the major river tributaries and bifurcations. In order to properly georeference each model another project was initiated to resolve the watershed hydrology at each model node. A GIS "robot" was created for this purpose which mapped points on a 1600 m (one mile) square grid mesh, superimposed upon water district boundary maps, to model nodes on the SJR and its major west-side tributaries. The robot searches the digital elevation map data to define a locus of low points along which surface runoff generated on irrigated land can flow to the river. The GIS provides information on interceptor ditches and other barriers to overland flow which can alter the routing of surface water return flows to CALSIM-II and DSM2-SJR model nodes.

A screenshot of the ArcObjects-based tool is shown in Fig. 7. The tool was developed using Visual Basic to build the georeferenced models in the GIS using a CAD flowchart representation of the CALSIM-II and DSM2-SJR models. APSIDE is not a network flow model but rather produces output on drainage flows and drainage salinity loads that are associated with individual water districts. The different model objects for CALSIM-II and DSM2-SJR (channel reaches, nodes, diversions, etc.) were created as separate feature classes within a feature database residing in the geodatabase. The tools enable the addition, removal, moving, and attribution of the objects.

Rather than build a new graphical data browser, the Department of Water Resources' VISTA software package was utilized which enables the graphing and tabular viewing of DSS data in a Java environment. VISTA was embedded in the interface code so that it can be invoked directly from either CALSIM-II or DSM2-SJR GIS-based GUI. Procedurally, one can select a number of network elements and view the associated hydrographic data (Fig. 7). The geodatabase format allows selection of the network elements into a "geometric network", which provides for relationship assignments between the different objects. For example, if one moves a network node,

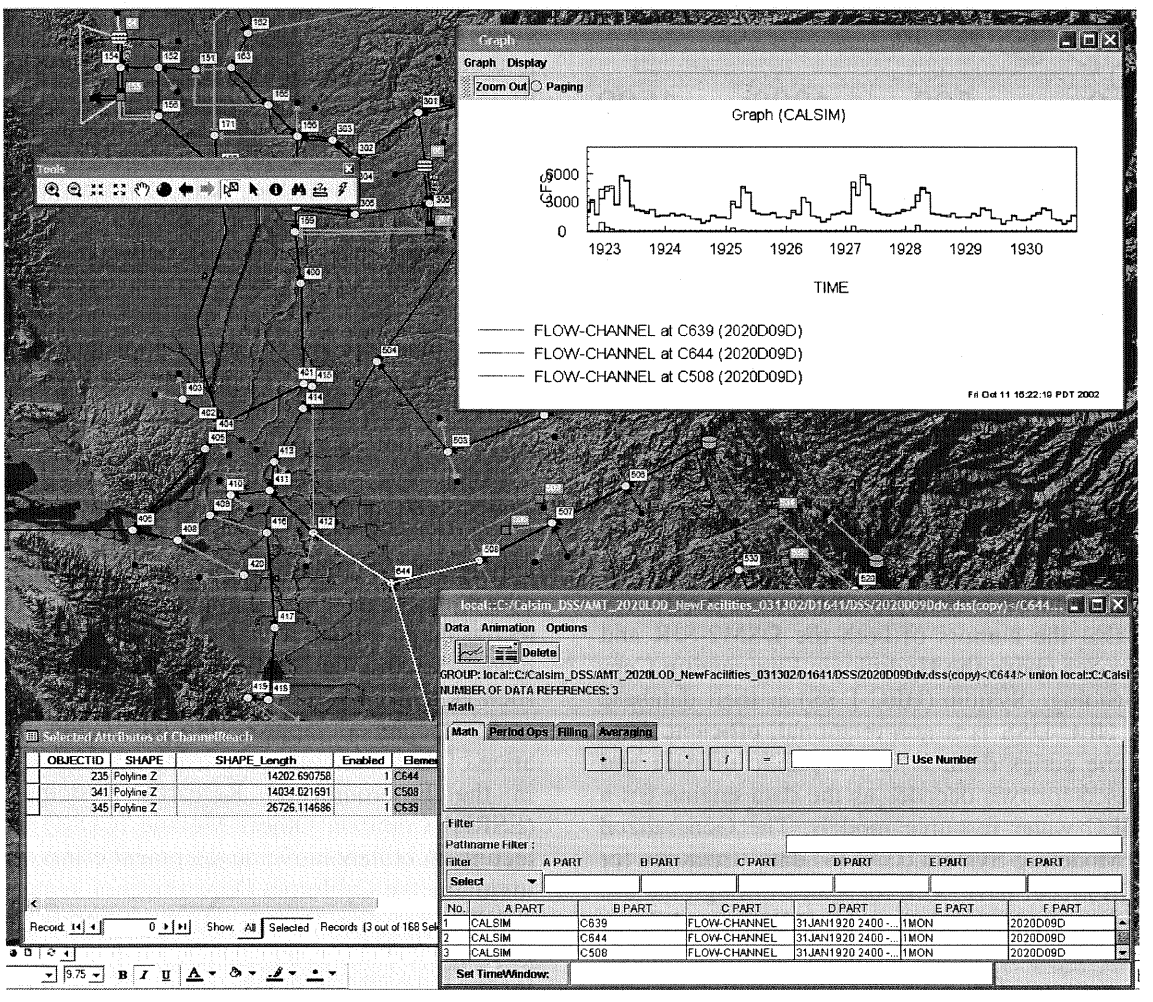

Fig. 7. A screenshot of the GIS ArcObjects based data and results browser. The tool was developed using Visual Basic to build the georeferenced models in the GIS using a CAD flowchart representation of the CALSIM-II and DSM2-SJR models.

the other reaches "rubber band" with it. Custom logical network tracing may also be performed. Users make queries based on date/time fields and extract hourly or monthly data. A statistical analysis tool is available within VISTA to view results as pie charts, stacked area charts, bar charts or line charts that can be either two-dimensional for maximum readability or three-dimensional for maximum effect. Users have the option to save this information in Excel-compatible Comma Separated Values (CSV) format for further processing in a spreadsheet such as Excel. The geodatabase and VISTA visualization tools are completely transferable to other models that use a DSS format for time series input data.

Future work on the impacts assessment toolbox will start within an updated screening study of GIS-based modeling frameworks in the public domain, similar to the study described by Argent and Grayson (2001). Modeling frameworks such as Tarsier (Watson et al., 2001) appear to have promise to overcome some of the fixed timestep limitations that compromised the application of the MMS/OUI toolbox (Leavesley et al., 1996) to the current application. Toolboxes that combine robust data storage, analysis tools and visualization systems that can deal with simulation models with varying time series data inputs will be key.

6. Summary

Model integration in this paper has described the use and linkage of newly developed water resource allocation, water quality and agricultural drainage economic models to address the impacts of future climate change on SJRB. The results of the studies described using downscaled end-member GCM outputs deviate somewhat from other published studies such as Lettenmaier and Ghan (1990) in that the impacts simulated from the drier of the two scenarios appear to be largely dampened by the resilience of the existing water storage and conveyance system. The major impacts appear to result more from flood events than water shortages whereby current reservoir operating rules allow insufficient storage to diminish warm winter runoff events. The large differences in future hydroclimate predicted by downscaling two GCM model outputs, which largely bracket the range of commonly cited GCM model outputs (i.e. PCM is the driest of the dry; HadCM is the wettest of the wet), show that there is still much uncertainty in the science of long-term climate forecasting. The science is insufficiently involved to provide direction to the Federal and State water planning agencies that manage developed water in the SJRB and in the State of California.

The DSM2-SJR and APSIDE model, although shown to provide sound simulations of water quality and production impacts to water shortages generated by the downscaled PCM model output after 2050, are not as critical to the analysis as they might have been under a more extreme hydroclimate. Neither DSM2-SJR nor APSIDE are particularly relevant to the scenario using HadCM downscaled output since San Joaquin River assimilative capacity would be in excess of that needed to induce actions to manage SJR water quality with additional release from New melons Reservoir.

The modeling toolbox described in the paper makes use of the new geodatabase architecture of Arc-Info GIS and graphical data browser tools that can be invoked from the model viewing window using shell scripts. The toolbox minimizes the time required for file manipulation and to formulate impact response scenarios allowing the analyst to simulate the impacts of global climate change on important California resources such as water supply, water quality, agricultural production and economic activity. These factors are key to the development of secondary and tertiary impact assessments dealing with issues such as the California fisheries, endangered species issues and socioeconomic welfare. Attempted model integration using the public domain toolbox MMS/OUI failed owing to a lack of compatibility of the monthly model timesteps and the input data time series supported by the MMS/OUI application. Instead a less elegant, but more robust, GIS-based data and analysis browsing system has been developed that has satisfied project goals.

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