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Model Integration For Assessing Future Hydroclimate Impacts On Water Resources, Agricultural Economic Sustainability And Environmental Quality

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Abstract: The US National Assessment of the Potential Consequences of Climate Variability and Change provides compelling arguments for serious consideration of actions and adaptive measures by countries around the world to better manage impacts on water resources, agricultural economic sustainability and environmental quality. National resource planning at this scale requires integrated impact analysis toolboxes to allow linkage and integration of hydroclimate models, linked surface and groundwater hydrologic models, economic and environmental impact models as well as techniques for social impact assessment. The rationale for selection of the simulation models is described as well as the challenges faced in linking the component models of the impacts assessment toolbox. Results from simulations performed with the impacts assessment toolbox are presented and discussed. After initially attempting model integration with a public domain, GIS-based modeling framework MMS/OUI an interactive, map-based web approach was developed instead owing to the non-conformity of database and model temporal scales.

Keywords: Climate change; water resources; model integration; impact assessment

1. INTRODUCTION

In the past decade concerns about possible global climate change and its impacts on water resources and agricultural production has stimulated interdisciplinary research in climatology and environmental science. 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 semi-arid San Joaquin River basin (SJR) 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 devastate 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 to evaluate water supply, agricultural production, environmental and social impacts to climate change in the SJR.

1.1 Background

The SJR contains two million hectares of crop land, receives an average of 20 cm 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 SJR 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 (Figure 1). During dry and critically dry years, flow in the SJR is dominated by

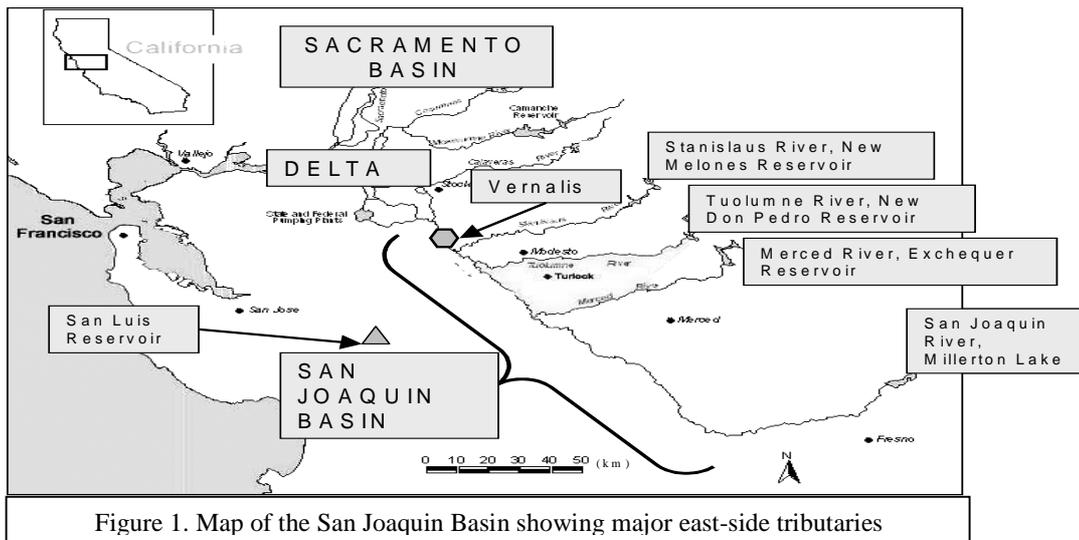


Figure 1. Map of the San Joaquin Basin showing major east-side tributaries

agricultural drainage flows from the west-side of the SJRB. 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

California water resources have been the subject of a number of climate change studies. A recent study used climate projection based on General Circulation Models (GCMs) with an annual one percent transient increase in atmospheric carbon-dioxide concentration. The GCMs generate climatic precipitation and temperature trends that can be mapped onto historical precipitation and temperature as input data to streamflow models in major tributaries of the SJR. The scenario studies suggest 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 (Miller et al. 2001). These studies ignore inter-annual variability and make only qualitative statements about the implications of these changes on water allocation, water quality, fishery and socioeconomic impacts.

2.1 Climate Simulations

Climate simulations for the current study were

performed by statistically downscaling large-scale data derived from General Circulation Models (GCMs) to nested limited area models (Miller et al. 2001). Outputs include regional hydroclimate - precipitation, snow budget, soil moisture, streamflow, temperature, wind, surface energy and water budgets (Miller et al. 2001). Two different GCMs were used in this study: The Hadley Centre Model (HadCM2) which produce 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 from the Intergovernmental Panel On Climate Change/ Third Assessment Report (IPCC 2001). Each GCM set of simulations included the historical period 1963-1992 and the projected periods 2010-2039; 2050-2079; 2080-2099. The 1963-1992 simulations are representative of a Present-day Climate (PC) and the 2010-2039; 2050-2079; 2080-2099 projections are representative of a Changed Climate (CC) with a one percent annual transient increase of atmospheric carbon dioxide concentration. Statistical downscaling of the climate projections to a 10 km resolution is based on linear regressions that are corrected using local observations (raingauge, thermometer) and topography (Miller et al. 2001). Watershed-mean-area precipitation and temperature time series were used as input to the NOAA/NWS Sacramento Soil Moisture Accounting Model and the Anderson Snow Model to obtain estimates of mean-monthly snowmelt, runoff, and streamflow timing. Streamflow perturbation functions for each headwater basin were developed based on the ratio of the CC to PC mean-monthly streamflow and applied to the entire SJRB using a similarity

approach. These functions were temporally aggregated to account for the Oct-Mar and Apr-Sept mean shifts in streamflow (Table 1), which were used as input to a water allocation model. The perturbation functions represent mean monthly sensitivity of runoff to climate change independent of water year-type.

Table 1. Streamflow perturbation functions

HadCM Streamflow ratios	2010- 2039	2050- 2079	2080- 2099
Oct - Mar	~2	~2	~5
Apr - Sept	~0.8	~0.8	~0.5
PCM Streamflow ratios	2010- 2039	2050- 2079	2080- 2099
Oct - Mar	~1	~1	~1
Apr - Sept	~0.5	~0.5	<0.5

3. WATER ALLOCATION AND STREAMFLOW SIMULATION

CALSIM-II is a hybrid linear optimization model which translates the unimpaired streamflows into impaired streamflows, taking into account reservoir operating rules and water demands exerted at model nodes, modified to reflect a year 2000 level of watershed development. 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. 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. Monthly climate change reservoir inflows were calculated by simply multiplying the reservoir's monthly present climate inflows with the monthly scaling factors (perturbation functions) of that reservoir's headwater basin or an associated basin

Simulations of water supply deliveries were made using CALSIM-II for both the HadCM2 and PCM GCM downscaled hydrology. In the case of the HadCM2 simulations rainfall runoff, snowmelt and reservoir inflow predicted by the downscaling and regional basin hydrology models are greater than the volumes produced under the base present

climate simulation. The deviation from the base case is most marked during dry years in river basins such as the Stanislaus (New Melones Reservoir) when water agencies typically announce reductions in contracted water supply. The models suggest flow volumes in excess of 300% of the annual mean flow during dry years (represented as min WY types in Figure 2). Under the wet and warm HadCM2 climate change model scenarios the likelihood of flooding for upper elevation river basins such as the Merced, where most precipitation accumulates as snow, is elevated with consequences for economic losses due to inundation. The PCM climate change scenarios show a small decrease in the annual volume of precipitation in the State.

CALSIM-II simulation runs show very little impact to flows in the San Joaquin River at Vernalis. The logic in the CALSIM-II model and the current model weights are designed to follow existing water agency guidelines. During dry and critically dry water year types municipal, industrial and environmental needs are given higher priority than agriculture leading to reductions in contracted water supply of up to 75%.

4. AGRICULTURAL PRODUCTION AND DRAINAGE SALINITY

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. APSIDE simulates agricultural yield and productivity response to water supply, irrigation water quality, root zone and groundwater salinity and predicts future agricultural drainage and water quality (Figure 3).

Subsurface drainage from west-side agricultural land has a significant impact on SJR water quality because of the marine origin of the west-side soils. West-side drainage flows annually contribute 60-70% of the salt and boron loading to the SJR as measured at Vernalis. In the absence of a means to export these contaminants, salt and boron builds up in the crop root zone and in the groundwater reducing crop yield, leading to reduced agricultural income and eventual land retirement when production costs exceed farm income. The crop production function contained within the APSIDE objective function attempts to maximize land productivity by minimizing costs of agricultural production and crop yield impacts due to salinity.

Reservoir Storage : New Melones Reservoir

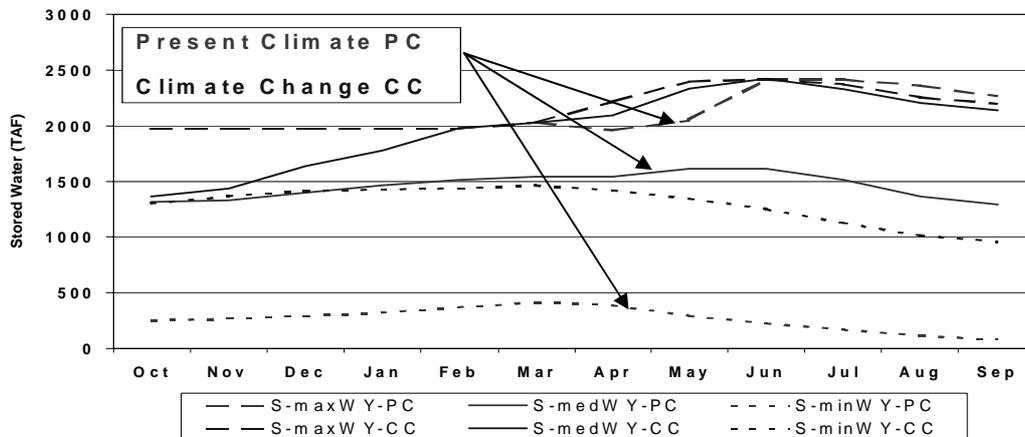


Figure 2. New Melones Reservoir storage under a HadCM2 CC scenario for different water year types.

In the PCM climate scenario, where a reduction in mean monthly precipitation produces a decline in reservoir storage in the CALSIM-II model, the results suggest an average annual reduction in water deliveries of about 50% to agriculture on the west side of the San Joaquin. These reductions in water deliveries do not affect drainage return flows in APSIDE— however water quality shows a dramatic increase as the model increases recycling of drainage water. The APSIDE model contains production costs associated with more than twenty combinations of irrigation and drainage practices ranging from low technology, low cost options such as half-mile furrow irrigation without drainage recycling to high cost subsurface drip irrigation. The model modifies irrigation and drainage practices in circumstances where there is economic advantage. 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.

5. RIVER FLOW AND WATER QUALITY SIMULATION

Drainage return flows generated by the APSIDE model must be routed to the SJR in order to determine the impact of these activities on river water quality. A one dimensional hydrodynamic flow and salinity model, DSM2-SJR (a version of the California Department of Water Resources' Delta Simulation Model extended and calibrated

for the SJR) is used to make these computations. The model calculates the load contributed from each source based on its flow and concentration using a mass balance accounting method. 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 reservoir release operations at New Melones Reservoir. One of the primary authorized uses of New Melones storage is for the maintenance of a 30-day running average electrical conductivity (salinity) 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.

6. MODEL INTEGRATION, FEEDBACK LOOPS AND ITERATION

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 is capable of producing a superior estimate of an important state variable. It is this aspect of model integration that is the most tedious and which works against the principles of modularity and object oriented model construction and use. Model integration was considered of highest priority for the impacts models, CALSIM-II, APSIDE and DSM2-SJR. These models collectively contain hundreds of decision variables many of which will

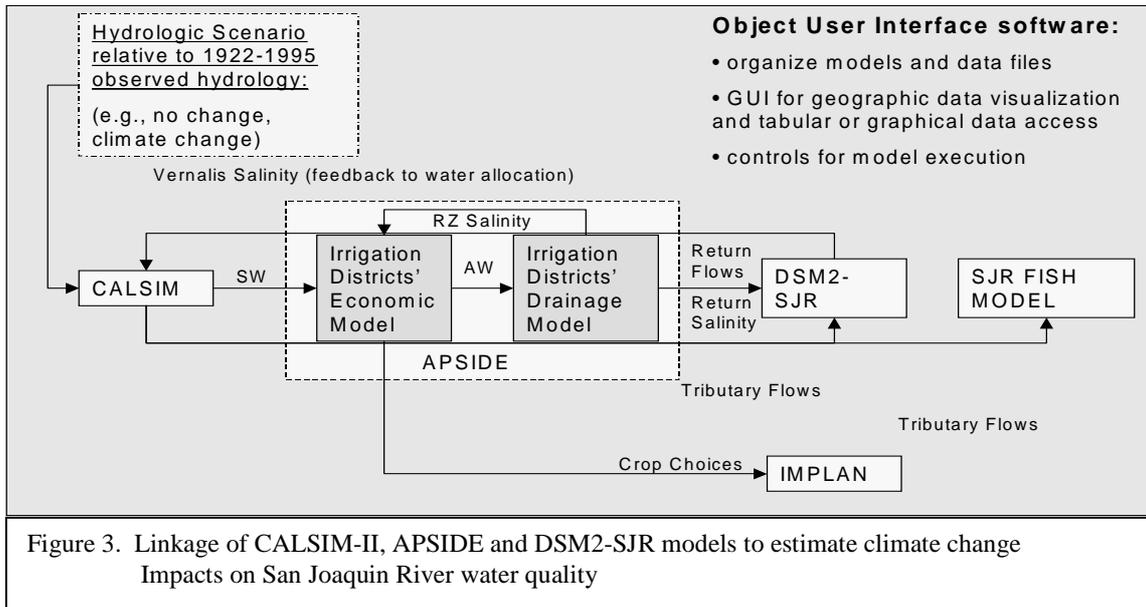


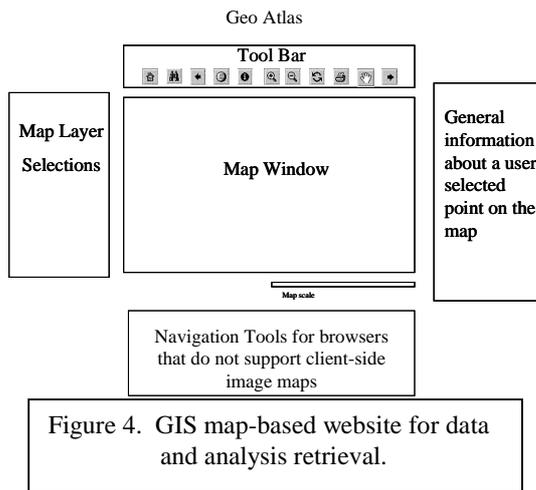
Figure 3. Linkage of CALSIM-II, APSIDE and DSM2-SJR models to estimate climate change Impacts on San Joaquin River water quality

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 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 resources 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 disaggregation 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 contemplated that would allow the data to be retrieved through interrogation of the base map and allows graphical output to be displayed at each element/node for each model.

7. 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 DSS 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. MMS/OUI was therefore rejected for our application. It may be unsuitable for projects where databases and model timesteps are not actively supported by the developers.

A less ambitious architecture has therefore formulated for the GUI using an interactive map-based website that allows users to explore, retrieve and display information such as georeferenced maps, three dimensional images and spreadsheet data. Microsoft's Active Server Pages technology (ASP) was used to create interactive and dynamic



web pages for the project. Instead of publishing static web pages, that always contain the same information, dynamic HTML pages were created containing embedded ASP code. When a user requests data from the model geo-database, the server executes the code contained in that page, extracts the relevant information from the geodatabase, reformats the data and displays it in a user-accessible HTML page. The website is configured in three components. The first provides access to project background, models and climate change scenarios. The second is interactive and map-based - check boxes and option buttons allow users to view base images of each of the models and any number of associated geo-referenced layers. Tools allow users to toggle map layers on and off, change color of map layers, zoom in and out, pan or shift the map, identify features and change scale units displayed. The third is database driven and consists of pull down menus whereby the users make queries based on date/time fields and extract hourly or monthly data. A statistical analysis tool is used to view results in the form pie charts, stacked area charts, bar charts or line charts that are either two dimensional (for maximum readability) or three dimensional (for maximum effect). Users have the option to save data as Excel compatible Comma Separated Values (CSV) files for spreadsheet processing and graphical display.

8. SUMMARY

The modeling toolbox described in this paper involves the integration of state-of-the-art resource management models newly developed within the State and Federal water agencies in California. 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. Integration using a public domain toolbox MMS/OUI failed owing to a lack of conformity to a database engine and model timestep that are supported by the application. Instead a less elegant but more robust web-based data and analysis browsing system has been developed that satisfies the project goals.

9. ACKNOWLEDGEMENTS

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