



Use of the Hydro-Salinity, Crop Production Optimization Model APSIDE to Validate Results from an Updated Regional Flow Model of the San Joaquin River Basin

Nigel W. T. Quinn^(✉)  and John Cronin

Lawrence Berkeley National Laboratory, Berkeley, CA, USA
nwquinn@lbl.gov

Abstract. APSIDE is an optimization model capable of simulating irrigation hydrology and agricultural production under saline conditions. The model has been used in the past to predict future agricultural production under future climate change in the San Joaquin River Basin of California (Quinn et al. 2004). In this study the model was used to query the results from a highly-regarded, published regional surface-groundwater flow model of the Central Valley of California – CVHM (Faunt et al. 2009) which includes the San Joaquin Basin. The APSIDE model was updated using recent aquifer and climate data and provided common initial conditions to allow a 53 year comparative simulation of the models. Model outputs for individual water districts for parameters such as deep percolation and upflux in APSIDE were compared to identical drained subareas within the CVHM model. The comparison showed that the APSIDE model produced lower values of deep percolation and upflux than CVHM. CVHM’s deep percolation values were 18% higher in Panoche WD, 40% higher in Broadview WD, 68% higher in San Luis WD, and 46% higher in Pacheco WD. Unlike the CVHM model that assumes fixed levels of irrigation and drainage technology and static average water district irrigation efficiency APSIDE will substitute more cost effective irrigation and drainage technologies based on the calculated future benefit stream relative to the cost of production and impact of salinity on crop yields. An unpublished recent update to the current CVHM model (CVHM-2) which substitutes actual irrigation diversion records from delivery canals rather than usually-reliable Agency records - produced water district irrigation diversions that were approximately 50% of the previously provided diversion data. The new model produces water district aquifer recharge estimates that correlate closely with APSIDE model output. This study demonstrates the successful use of a complementary agricultural production optimization and hydro-salinity simulation model to help validate a radical and important update to a widely distributed and well-accepted regional flow groundwater model.

Keywords: Salinity · Crop production · Optimization · Drainage · Irrigation

1 Introduction

In California, agriculture is the largest user of water, an important source of employment and income for many regions, and source of tax revenues for the state. Statewide irrigated agriculture revenues are approximately \$22 billion per year (www.opr.ca.gov) supporting 300,000 to 450,000 jobs. The population of California is forecast to exceed 65 million by 2050, implying significant increases in urban water demand and use. Further complicating the picture is an increasing awareness of the importance of the Sacramento-San Joaquin Delta as a key ecosystem for native fish and the importance of water quality, particularly salinity, in developing long-term sustainability plans for the Region. The use of surface and groundwater simulation models that incorporate economics can be useful for policy analysis and to help balance competing uses for water supply and protecting water quality. An ideal integrated modeling framework incorporates the dynamics of the interaction between the environment, urban and agricultural stakeholders providing a decision analysis tool for evaluating the economic benefits and costs of water policies and policy-induced changes to the current system (Howitt et al. 2010). This paper describes the use of a unique hydro-salinity and economic simulation tool APSIDE (Agricultural Production Salinity Irrigation Drainage Economics), capable of simulating agricultural production and land use in the salinity-impacted western San Joaquin Valley of California, to query the results from a widely-accepted regional flow model of the Central Valley (Sacramento and San Joaquin Basins), developed by the US Geological Survey (USGS). This study also serves to validate preliminary results from a recent update to the USGS Central Valley Hydrologic Model (CVHM), based on raw diversion data obtained from the Water Authority charged with operating the water distribution system rather than the water agency traditionally charged with furnishing this data to the public.

Hydrological models used for planning, studies around the world often achieve legacy status – the datasets used to calibrate and validate these models are rarely questioned, especially when the models are developed by science-based institutions such as the US Geological Survey in the USA. Although subsequent studies by other agencies, universities and consultants may produce anomalous results – such is the inertia of the model development and review process that these models become a de-facto “gold standard” against which other modeling efforts are compared. Some datasets such as crop coefficients used for computation of crop-based evapotranspiration are based on experiments that are decades old and crop cultivars that have since been replaced by more robust and drought-tolerant strains. Similarly, methods for flow estimation in canals and at diversion structures have been replaced by more advanced acoustic Doppler technologies that provide more accurate accounting. Greater use of complementary modeling and simulation tools can help to challenge the validity of certain datasets and assumptions made in these important legacy models leading to improved outcomes.

2 Background

Technological innovation does not typically succeed without being cost effective – hence the consideration of economics is paramount to guide basin-scale water quality management. The most obvious technology solutions involve: (a) increasing irrigation efficiency by re-using drain water to blend with good irrigation water; (b) growing salt-tolerant crops; (c) improve on-farm drainage management. One can also fallow or retire the land and sell the water, or utilize the assimilative capacity of the San Joaquin River in a coordinated fashion to discharge limited amounts of salt load without exceeding salinity objectives. A changing climate can have an effect on water availability as well as temperature, which in turn can have an effect on plant yields.. Understanding water availability and water quality, in particular, is critical to understanding long-term agricultural production in the San Joaquin Valley.

The west-side of the San Joaquin River Basin (SJR) receives limited rainfall and relies on additional water supply from the Delta to meet the needs of irrigated agriculture. Salts are imported with irrigation water - changing water availability and water salinity can have a direct effect on yields. Applied irrigation water is subject to the processes of direct evaporation from the soil surface and transpiration from the crop. Pure water is evaporated, leaving behind the salts in irrigation water. Over time, these salts can accumulate in the soil and groundwater and can affect agricultural yields. Excess water can leach out salts in soil profile - however excess water is limited in the SJR to effect this leaching. Schoups et al. (2005) showed a steady cumulative increase in net salt in SJR soils and groundwater – which has the potential to diminish irrigation sustainability.

To address salinization related problems on the west-side of the SJR - drainage management measures have been suggested as follows:

- Reduction of deep percolation (the downward movement of water below the root zone, past drains to the local groundwater system) through the adoption of water conserving irrigation technologies and practices, better irrigation scheduling and changes in cropping practices (Grismar 1990).
- Reuse of drain water, through the use of salt-tolerant crops and agro-forestry.
- Manipulation of the water table to meet part of the crop evapotranspiration requirements.
- Conjunctive use of groundwater to meet a portion of crop needs.
- Improved instrumentation and monitoring systems to produce accurate and timely information and improve access to this information by growers.
- Development and installation of real-time monitoring systems to progressively evaluate changes in soil and water quality in the terrestrial and aquatic ecosystems over time.

High irrigation efficiencies may actually lead to higher concentrations of salt in deep percolation. Efficient irrigation methods are those with deep percolation of less than 10% of the irrigation applied water (Hanson et al. 2014). Doneen (1967) reported that in the SJR the salinity of soils covered with native vegetation is generally lower than soils in irrigated areas. Irrigation water normally contains from 0.06 to 3.95 tons of salt per acre-ft of water (1 ton/acre-ft = 0.82 kg/m³) and crop requirements are between 2.03 to

3.05 acre-ft/acre (1 acre-ft/acre = 3048 m³/hectare) to fulfill evaporation requirements. Thus, this amount of irrigation water may add approximately from 0.12 to 1.29 tons of salts/acre (1 ton/acre = 2242 kg/ha) annually anywhere (Rhoades and Suarez 1977). Groundwater can become degraded by salinity through irrigated agricultural practices by three process (1) salt concentrated is due to the uptake of water by plant, (2) salt moves down from the unsaturated zone into groundwater (saturated zone) because of leaching and mixing of subsurface saline water with higher quality groundwater and (3) enhanced percolation of saline water into the lower zone as a result of groundwater pumping for irrigation. (Suarez 1989, Tanjii 1990).

3 Modeling of Hydrosalinity in West-Side Irrigated Agriculture

A state-of-the-art model known as the Central Valley Hydrologic Model, (CVHM) was developed by the US Geological Survey (USGS) and simulates the effects of hydraulic conductivity, irrigation, streamflow losses, wells, and other parameters on groundwater flow (Faunt et al. 2009). The CVHM model application uses the recently published FORTRAN hydrologic code, MODFLOW-OWHM which contains the Farm Management Process – a pre-processor that simulates agricultural irrigation hydrology (Hanson et al. 2014). This model was created and calibrated using historic observations, calculations, and measurements of the factors affecting hydrology, including geological and meteorological data from April 1961 until December 2013. Canal diversions to individual water districts were obtained from the Central Valley Operations Office of the US Bureau of Reclamation which has been providing this data to the public for many decades as is considered the most reliable source of this information. The model divides the valley into one- mile (1.6 km) square cells which form a grid 98 cells wide and 441 cells long. The grid is also 10 layers deep in the vertical dimension, enabling the user to analyze subsurface water flow separately from surface water flow.

Models such as CVHM have been used for long-term planning studies provided a suite of realistic future conditions can be developed including future hydrologic conditions, land use, agricultural production and regulatory constraints on agricultural production. However models such as CVHM assume static conditions for irrigation management and technology. Since detailed water district cropping data has typically only been publicly available in 5–7 year intervals (now available annually) models such as CVHM have typically also assumed static cropping mixes within each modeled subarea. More realistic tracking of agricultural production on the west-side of the SJRB requires a simulation tool that recognizes relationships between crop markets and costs of production, the impacts of investments in improved irrigation and drainage technologies on irrigation hydrology and soil salinity and the relationship between soil salinity and crop yield (Maas and Hoffman 1977) which can promote crop substitution over time to more salt tolerant crops and crop cultivars. The APSIDE (Agricultural Production-Salinity-Drainage-Economics) Model (Figs. 1a and 1b) fulfills this purpose allowing more realistic future irrigation hydrology projections to be made on the west-side of the SJRB. APSIDE was used in this study to develop comparative irrigation hydrology, drainage and aquifer recharge estimates over a 53 year simulation period.

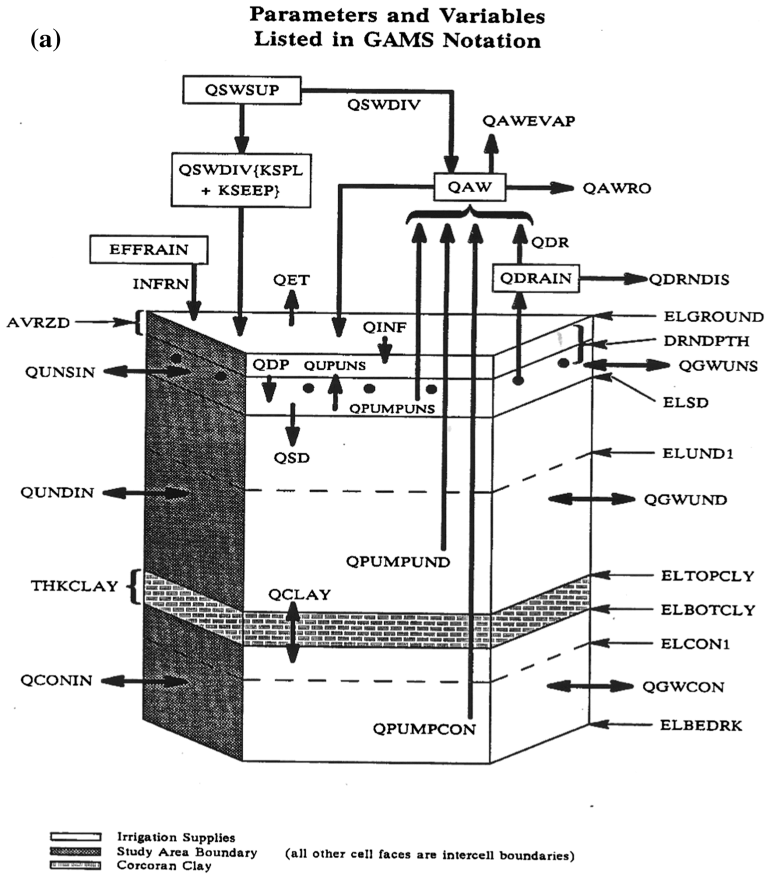


Fig. 1. (a) APSIDE conceptual model for flow showing parameters and variables listed in GAMS notation. Lateral flow between adjacent water districts are simulated as “equations of motion” or head-dependent fluxes between the centroids of each subarea.

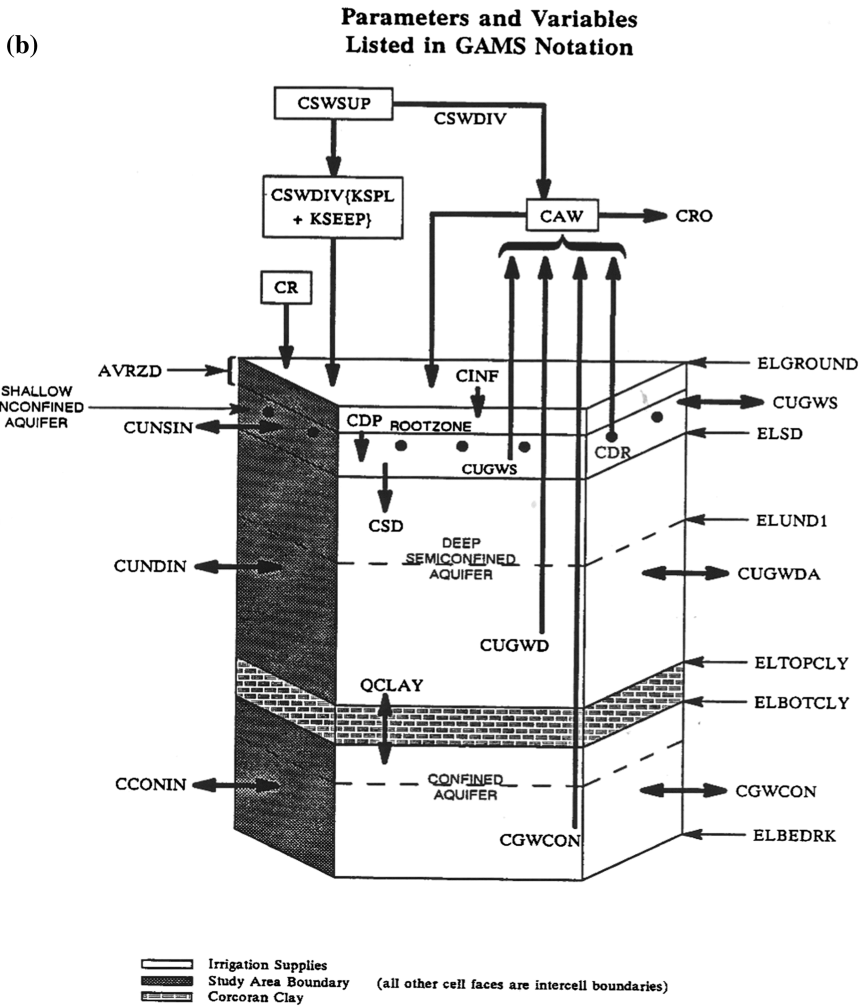


Fig. 1. (b) APSIDE conceptual models for salinity showing parameters and variables listed in GAMS notation. Lateral movement of salt between adjacent water districts is driven by the hydrology and hydraulic flux between the centroids of each area.

3.1 APSIDE Model Features

Resource analysts face a fundamental difficulty in modeling regional production activities: simplifications used to keep a model manageable by reducing computation and data requirements also prevent it from reproducing the variety and proportions of activities actually observed (Hatchett et al. 1989). These simplifications also often omit important cost differences that influence production patterns. Flexibility constraints can force regional activities to approximate observed levels, but then these constraints prevent the model from adjusting very much to policy changes.

APSIDE is an agricultural production optimization model, written in the GAMS language (GAMS 1998), that simulates hydrology and salinity (Figs. 1a and 1b) on the west-side of the SJRB. The model proved useful for understanding water resource utilization in the San Joaquin basin in response to potential future climate change and long term surface water allocations within the federal Central Valley Project service area (Quinn et al. 2004). The motivation for enhancing and updating the APSIDE model is to provide a decision tool that simulates long-term agricultural production taking into consideration the availability of groundwater resources, the cost of pumping and the impacts of salinity in groundwater pumpage. The genesis of the APSIDE model were two models - the Statewide Agricultural Production model (SWAP), which forecasts future agricultural production as a function of commodity price projections, anticipated changes in the costs of production and surface water supply availability and the Westside Agricultural Drainage Economics Model (WADE), which makes projections of future agricultural drainage and farm income resulting from policies that affect agricultural production and investments in irrigation and drainage technology (Hatchett et al. 1989). The agricultural production simulation algorithms utilize a technique known as Positive Mathematical Programming (PMP), which can reproduce observed activities quite precisely without a large increase in required data and without restricting the model's ability to shift activities as conditions change (Howitt 1995).

The PMP technique relies on the concept of dual variables, or shadow prices, to infer otherwise unobserved cost differences among activities. A PMP model of regional crop production is implemented in two stages. The first, or calibration, stage is a traditional programming model which restricts crop acreage to observed levels. The dual values associated with the acreage constraints are the marginal changes in the objective (usually net revenue) function from small changes in the constraints. The dual values are positive when the constraints force a lower acreage of a particular crop than an unrestricted model would calculate (and negative when the constraints force a higher acreage). The second stage of PMP re-solves the first stage model after making two important changes. First, the crop acreage constraints are removed. Then the dual values from the calibration stage are used to calculate a linear marginal cost function for each crop activity. Integrating the marginal cost gives a total cost quadratic in crop acreages. The quadratic form is then appended to the objective function. The cost function intercept and slope values for each crop and region, obtained for the PMP algorithm during calibration of the APSIDE model are used to estimate proxy crop activity levels at the beginning of each year simulated by the model. The PMP algorithm will duplicate the crop mix from the restricted calibration model and will also allow smooth changes in crop levels as conditions or policies change.

Five proxy crops were considered in the APM; alfalfa (including hay and seed crops, rice, irrigated pasture); trees, fruits and nuts (almonds, apples, apricots, olives, peaches, walnuts, pistachios, grapes, nectarines, oranges); row crops (cotton, sugarbeets, processing tomatoes, corn, sorghum); grain crops (wheat, barley, oats.) and vegetable crops (beans, melons, lettuce, spinach, onions, garlic, broccoli, peas). These proxy crops are assigned average hydrologic characteristics of the group they represent.

The PMP cost function were calculated separately for overspecialized and under-specialized crops grown in the study subareas. Overspecialized crops are those which are so profitable that greater quantities would be produced according to the model than would normally be observed. Hence an increment was added to the production costs of these crops to lower their activity to the observed marginal profitability levels. Conversely, incremental increases in revenue were added to the production of under-specialized crops in order to match the observed marginal values. The increments added are not fixed, but rather vary in quadratic fashion with crop acreage.

For the SWAP and WADE models - the agricultural production submodels considered the summer (irrigation) season and the winter (rain and pre-irrigation) season of each year, interacting sequentially with the hydrology and salinity models. In the APSIDE model the sequential seasonal hydrology and salinity models were transformed into a discrete monthly timestep hydrosalinity submodel that solves simultaneously in order to capture more of the complexity of irrigation hydrology and water quality within the SJRB - where water supply to agriculture is subject to frequent perturbations in water quality. This has allowed the APSIDE model to be used in the past in integrated model-based planning studies of the Basin that consider future potential climate change (Quinn et al. 2004).

3.2 Comparison of Model Simulations

The APSIDE model was run for a period of 53 years for four water districts in the Grasslands Subarea on the west-side of the SJRB (Fig. 2). The APSIDE model application used the same water table, cropping and irrigation water use efficiency initial conditions as the USGS CVHM (Faunt et al. 2009) model. In the APSIDE model aquifer characteristic data such as aquifer hydraulic conductivity, specific yield and storativity was averaged (lumped) for each water district in the study –whereas CVHM can assign unique values for each one mile square model cell.

The APSIDE and CVHM model outputs for deep percolation and upward capillary flow were compared. These outputs are the most important factors impacting water tables, tile drainage, soil salinity and crop yield. The comparison showed that, on average, APSIDE produced lower values of deep percolation and groundwater upward capillary flow (upflux) than CVHM (Fig. 3). On average, CVHM's deep percolation estimates were 26% higher in Panoche WD, 12.9% higher in Broadview WD, 45.3% higher in San Luis WD, and 51.3% higher in Pacheco WD (Fig. 4). (Broadview gets no surface water deliveries having sold their federal water rights to an adjacent water district more than a decade ago). Upflux estimates are similarly higher for the CVHM model (Fig. 5) – Pacheco WD shows the greatest difference between CVHM and APSIDE model estimates. Water deliveries (canal diversions) to each of these water districts were derived from publicly available US Bureau of Reclamation Central Valley Operations bulletins.

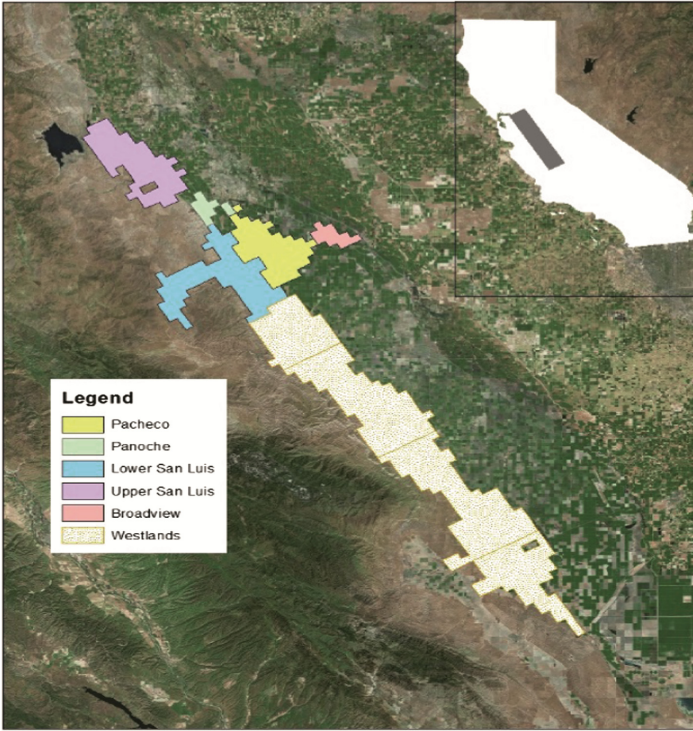


Fig. 2. Water districts within the salinity impacted study area on the west-side of the SJRB, California. Results from Panoche, Pacheco, Broadview and San Luis Water Dis-tricts are the subject of the analysis in this study.

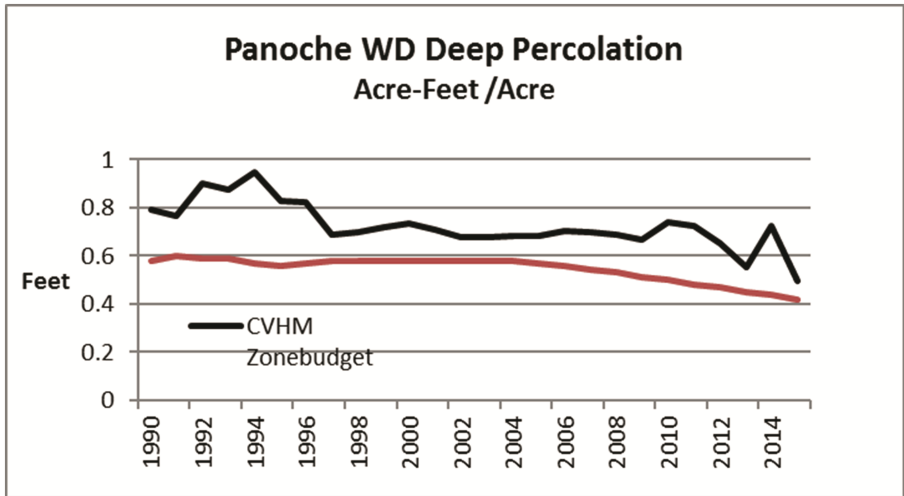


Fig. 3. Comparative results using APSIDE and CVHM models showing more real-istic deep percolation estimates using APSIDE agricultural production optimization algorithms using PMP.

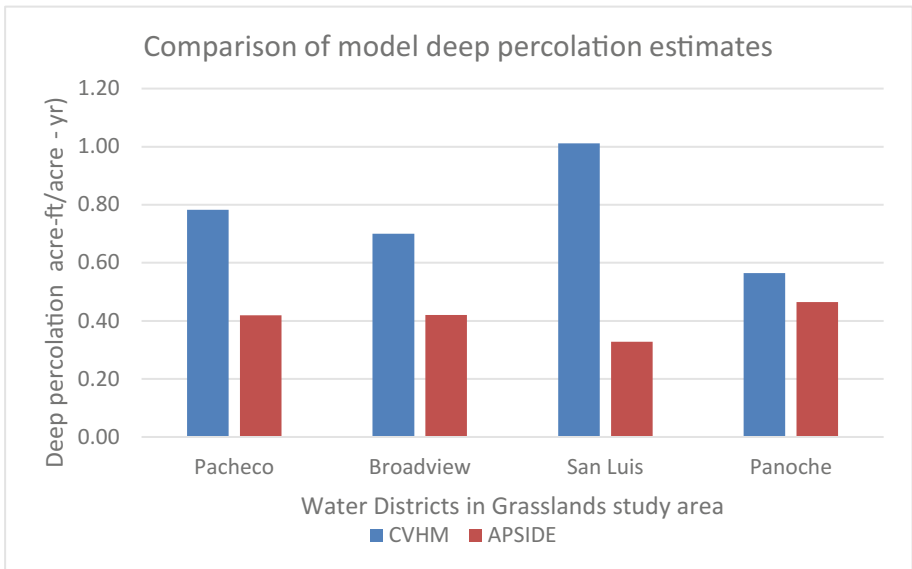


Fig. 4. Comparison of deep percolation estimates between CVHM and APSIDE models. Higher deep percolation rates raise water levels, increasing subsurface drain-age discharge production and salt load export to the San Joaquin River.

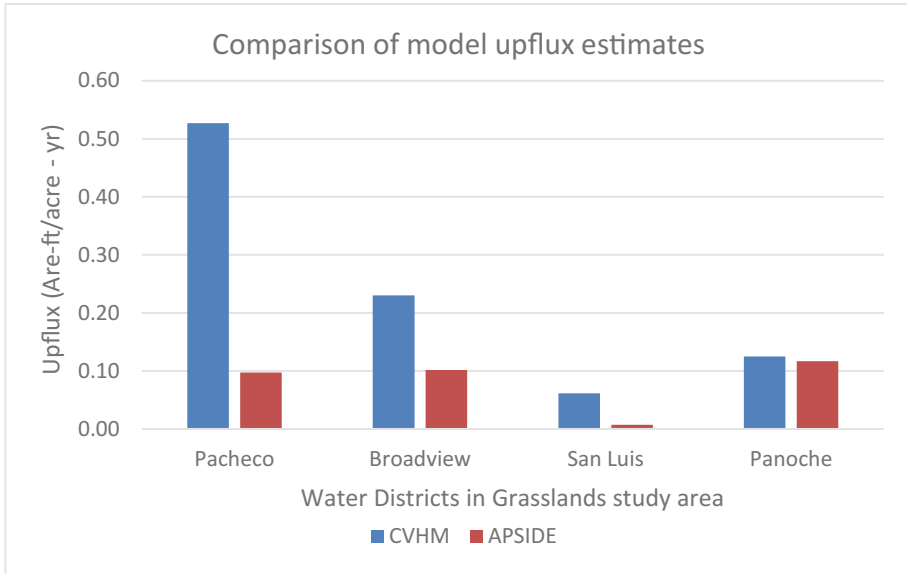


Fig. 5. Comparison of groundwater upflux estimates between CVHM and APSIDE models – higher groundwater upflux increases precipitation of salt in the crop root zone.

The APSIDE model bases water deliveries on water requirements which in turn are based on crop selection and irrigation management technology and practices. Hence differences in the APSIDE and CVHM model estimates can be ascribed either to the inability of the CVHM model to track changes in crop selection and irrigation water use efficiency resulting from changes in crop root zone salinity or to problems in the reported irrigation water deliveries (diversions) to each water district. One of the novel features of the APSIDE model is its ability to adapt irrigation and drainage technologies in response to production costs, the water saving potential of improved techniques and salt load discharge constraints that limit the export of salts to the San Joaquin River. As the cost of drainage disposal increases over time the APSIDE model substitutes more water conserving irrigation technologies such as sprinkler and drip irrigation for furrow and basin flooding techniques – improving irrigation water use efficiency over time. Using the same irrigation diversion data the APSIDE model still derived optimal yields and farm income by reducing irrigation application resulting in deep percolation rates that were as much as 50% lower than those produced by CVHM.

The deep percolation values in APSIDE and CVHM were further compared to reported data from Panoche and Pacheco Water Districts. Pacheco Water District reported year 2010 deep percolation values of 1770 acre-feet on 4080 acres of irrigated land (Panoche Water District 2015). This corresponds to a deep percolation of 0.43 acre-feet per acre. This aligns fairly closely to APSIDE’s predicted value of 0.42 acre-feet per acre for Pacheco Water District (Westcot et al. 1994).

3.3 CVHM-2 Diversion Data Update

Difficulties in obtaining good model calibration for the west-side of the San Joaquin Valley in CVHM, particularly in the simulation of subsurface tile drainage, prompted the USGS to seek better quality data as part of the development of an updated simulation model of the Central Valley CVHM-2. The new model increased the number of vertical layers from 10 to 13, improved the accuracy of cropping data by incorporating data obtained directly from water districts and substituted public records from the US Bureau of Reclamation's Central Valley Operations office for raw canal turnout records compiled by the Water Authority responsible for daily operations along the Delta Mendota Canal – the main conveyance for federal water deliveries. These data had to be further processed to associate each irrigation turnout with a delivery point within each water district subarea. Preliminary (unpublished) model results shared by colleagues in the USGS have shown that average water diversions to the water districts that were the subject of this study decreased up almost 50%. Similarly the CVHM-2 model estimates of aquifer deep percolation were reduced by an equivalent amount. These same colleagues report that the CVHM-2 model achieved a better calibration for west-side San Joaquin Valley hydrology than the original CVHM model – much of it ascribed to the more realistic diversion data. These results correlate much more closely with the results from the APSIDE model.

4 Summary and Conclusions

The time and effort involved in developing comprehensive regional surface and ground-water simulation models often confers a legacy status to these models whereby they become the “gold standard” against which subsequent modeling studies are compared. This is accompanied by a reluctance or “inertia” to revisit model assumptions or the data used to develop the model – even though these further studies might suggest fundamental problems. The use of complementary simulation models and analytical tools to test assumptions and the conceptual hydrology underlying these legacy models has significant, unrealized potential to promote better outcomes and result in more accurate decision tools. This study has provided an exemplar of the use of a simple agricultural production optimization and hydro-salinity simulation model that utilizes a unique normative calibration technique to allow realistic simulation of future changes in agricultural land use and investments in irrigation and drainage technology over long-term planning horizons. The PMP algorithm allows substitution of irrigation and drainage technologies while calibrating crop production shifts to field observations – capturing some of the socioeconomic factors known to effect on-farm decision making. The APSIDE model can be applied to any problem involving irrigated crop production under saline conditions provided data are available for annual cropping and the costs of irrigation and drainage technology substitution are available. Soil and aquifer characteristic data including root zone and aquifer salinity data are also needed.

References

- Doneen, L.D.: Quality of percolating waters, I. properties of deep substrata materials in the west side of the San Joaquin Valley, California. *Hilgardia* **38**(9), 285–305 (1967)
- Faunt, C.C., Hanson, R.T., Belitz, K., Schmid, W., Predmore, S.P., Rewis, D.L., McPherson, K.R.: Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley (Chapter C). In: Faunt, C.C. (ed.) *Groundwater Availability of the Central Valley Aquifer*, pp. 121–212. U.S. Geological Survey Professional Paper 1776, California (2009).
- GAMS Inc., Brooks, A., Kendrick, D., Meerhaus, A., Raman, R.: *GAMS: A User's Guide*. GAMS Development Corp., Washington, DC (1998)
- Grismer, M.E.: Leaching fraction, soil salinity, and drainage efficiency. *Calif. Agric.* **44**(6), 24 (1990)
- Hanson, R.T., Boyce, S.E., Schmid, W., Hughs, J.D., Mehl, S.M., Leake, S.A., Maddock III, T., Niswonger, R.G.: *One-Water Hydrologic Flow Model (MODFLOW-OWHM)* (2014)
- Hatchett, S.A., Quinn, N.W.T., Horner, G.L., Howitt, R.E.: A drainage economics model to evaluate policy options for management of selenium contaminated drainage. Toxic substances in agricultural water supply and drainage. In: *Proceedings of the Second Pan American Regional Conference on Irrigation and Drainage*, Ottawa, Ontario, 8–9 June 1989
- Howitt, R.E.: Positive mathematical programming. *Am. J. Agric. Econ.* **77**, 329–342 (1995)
- Howitt, R.E., et al.: Economic modeling of agriculture and water in California using the statewide agricultural production model. *California Water Plan Update 2009*, vol. 4, pp. 1–25 (2010). http://www.waterplan.water.ca.gov/docs/cwpu2009/0310final/v4c04a02_cwp2009.pdf
- Maas, E.V., Hoffman, G.J.: Testing crops for salinity tolerance. *Water Management Plan*, U.S. Salinity Laboratory, USDA-ARS, Pacheco Water District, pp. 27–29 (1977)
- Panoche Water District. Personal communication Marcos Hedrick, Panoche Water District. Panoche Water District keeps irrigation and drainage records for Pacheco Water District (2015)
- Quinn, N.W.T., Brekke, L.D., Miller, N.L., Heinzer, T., Hidalgo, H., Dracup, J.A.: Model integration for assessing future hydroclimate impacts on water resources, agricultural production and environmental quality in the San Joaquin Basin. *Calif. Environ. Model. Softw.* **19**, 305–316 (2004)
- Rhoades, J.D., Suarez, D.L.: Reducing water quality degradation through minimized leaching management. *Agric. Water Manag.* **1**(2), 127–142, 143, 305–316 (1977)
- Suarez, D.L.: Impact of agricultural practices on groundwater salinity. *Agric. Ecosyst. Environ.* **26**, 215–227 (1989)
- Schoups, G., Hopmans, J.W., Young, C.A., Vrugt, J.A., Wallender, W.W., Tanji, K.K., Panday, S.: *Proc. Natl. Acad. Sci.* **102**(43), 15352–15356 (2005)
- Tanjii, K.K.: Nature and extent of agricultural drainage. In: Tanji, K.K. (ed.) *Agricultural Salinity Assessment and Management*. American Society of Civil Engineers Manuals and Reports of Engineering Practice, no. 71, pp. 1–17 (1990)
- Westcot, D., Steensen, R., Styles, S., Ayars, J.: *Grassland Basin Irrigation and Drainage Study*. Irrigation Training and Research Center, San Luis Obispo (1994). Accessed 04 July 2015