Supporting Text

History of Irrigation

Irrigation on the Westside began at the end of the 19th century with flood irrigation using Sierra Nevada rivers runoff (1). Early irrigation was limited to the valley by gravity diversions. The next phase of irrigation development was characterized by intense groundwater pumping, starting in the 1920s, which prompted an increase in irrigated acreage westward toward the Coast Range foothills, increasing irrigated area from ≈50% (1940) to 70% (1950) of total land area. The increase in irrigated area by pumping decreased the hydraulic heads in the confined aquifer and caused severe land subsidence. Completion of the Federal and State Water Projects resulted in increased deep percolation rates. Combined with a sharp decrease in groundwater pumping, it caused a rise of the water table over much of the area. From 1958 on, rising water tables required the installation of subsurface drain pipes in some regions to keep salts and the water table out of the root-zone (RZ). The discovery of bird deformities in Kesterson National Wildlife Refuge in 1983 restricted drainage in some areas and completely shut down drainage in other parts of the study area. Subsequent investigations by the San Joaquin Valley Drainage Program resulted in the Rainbow report (2) that listed alternative in-valley management recommendations for a sustainable solution of the drainage problem in the San Joaquin Valley. These recommendations include increasing irrigation efficiency, growing alternative more-salt-tolerant crops, drainage water reuse, the collection of drainage water in evaporation ponds, land retirement, and increased groundwater pumping. In 1992 the Central Valley Project Improvement Act (CVPIA) required the transfer of 800,000 acre-feet of water per year from agriculture to environmental uses. Consequently, some farmers were limited to use either groundwater or recycled drainage water for irrigation, thereby increasing soil salinity.

Hydrogeology and Soils

The semiconfined aquifer consists of three hydrogeologic units: Coast Range alluvium, Sierran sand, and flood-plain deposits (3). The Coast Range alluvium is comprised of oxidized alluvial fan material deposited by intermittent streams originating in the Coast Ranges. These fans include, from north to south, Little Panoche Creek, Panoche Creek, and Cantua Creek fans. The deposits are mainly sand and gravel at the fanheads and along stream channels and are mainly silt and clay in the interfan and distal fan areas. Coast Range alluvium is 250 m thick along the Coast Ranges and thins to zero near the valley axis, where it interfingers with Sierran sand. The Sierran sand consists of well-sorted, coarse sand deposits derived from the Sierra Nevada to the east. The flood-plain deposits overlie the Sierran sand and consist mainly of clay and silt. The lower confined zone beneath the Corcoran clay has a thickness of 200–1,000 m.

The alluvial soils derived from Coast Range alluvium are generally fine-textured soils (Fig. 1*B*). Fig. 5 presents the distribution of soil salinity, soil sodium adsorption ratio (SAR), calcite content, and soil cation exchange capacity (CEC), using data from the 1992 western Fresno County soil survey (4). Salts are derived from various natural and anthropogenic sources. First, all waters, including snowmelt water that is the dominant irrigation water source in the San Joaquin Valley, contain salts that ultimately accumulate or pass through the irrigated soils and regional groundwater systems. Second, the soils on the west side of the San Joaquin Valley are derived from marine sedimentary rocks that contain both gypsum and calcite, which upon dissolution increase salinity of both the soil and shallow groundwater.

Agriculture and Water Resources

Irrigated agriculture in the western San Joaquin Valley occurs mostly in large holdings owned by big corporations. Cotton is the major crop grown, with lesser areas planted with tomatoes, melons, vegetables, and orchards. Salt-tolerant crops such as cotton, wheat, and alfalfa are grown downslope where the water table is shallow, whereas more salt-sensitive crops such as tomatoes and melons are grown in higher landscape positions in the western part of the study area. Orchards are common on the deep, coarse soils west of highway I-5 (Fig. 1*A*). Crop rotations are practiced to sustain fertility and control crop pests. A variety of irrigation methods are used, including furrow irrigation, sprinkler, and drip systems. Irrigation scheduling consists of a preplant irrigation applied in the late winter or early spring to wet the seed bed and flush the salts out, followed by periodic applications during the summer growing season. Subsurface tile drains were installed starting in 1958, for a total of ≈135,000 acres to control shallow water tables in the northern irrigation districts. On-farm drainage systems consist of a parallel network of perforated drain laterals, typically 1.8–2.7 m below the surface, and spaced horizontally from 30 to 180 m apart. Part of Westlands water district was actively drained from 1981 to 1985, until the discovery of bird deformities in nearby Kesterson Reservoir.

The average annual rainfall is 203 mm, most of it falling in the winter. Rainfall is slightly acidic and has a very low salinity of the Na/Cl type (Table 1). The main source of irrigation water is from the Delta–Mendota Canal, operational since 1953, and the California Aqueduct, which delivered irrigation water starting in 1967 (5). Groundwater for irrigation is primarily pumped from the confined aquifer below the Corcoran Clay. Because pumped groundwater is generally more saline than surface water, the salinity of the infiltrating water increases as groundwater is substituted for surface water, as happens during drought years. In Broadview water district (Fig. 1*A*), part of the subsurface drainage water is collected and mixed with surface water for irrigation reuse.

Hydrologic Modeling

It is only recently that computer hardware is sufficiently developed to solve the highly nonlinear complex soil chemistry and groundwater problems across such a wide range of spatial and temporal scales. This problem includes the need to incorporate computer-intensive parameter optimization techniques to match observed with simulated hydrologic data. The MOD-HMS model (6) solves the following equation:

$$\frac{\partial}{\partial x_i}\left(K_i k_{rw}\frac{\partial h}{\partial x_i}\right) - W = n\frac{\partial S_w}{\partial t} + S_w S_s \frac{\partial h}{\partial t}. \quad \textbf{[1]}$$

In Eq. **1**, x_i is the Cartesian coordinate [L], with i = 1,2,3 corresponding to the three major axes ($x_1 = x$, $x_2 = y$, $x_3 = z$); t is time [T]; K_i are the principal components of saturated hydraulic conductivity along the x, y, and z axes, respectively [L/T]; k_{rw} is the relative hydraulic conductivity that is a function of degree of water saturation (–), $S_w = \theta/n$, where θ is volumetric moisture content and n is porosity; h is total hydraulic head [L], so that $h = \psi + z$, where ψ and z denote the soil water pressure head and gravitational head [L], respectively, with z defined positive upwards; W is a volumetric water flux per unit volume, representing sources and/or sinks [1/T]; and S_s is the specific storage of the saturated porous material [1/L]. For each grid cell, the left-hand side represents boundary fluxes due to (*i*) head gradients as described by Darcy's law and (*ii*) sources (e.g., injection well) and sinks (e.g., evapotranspiration, subsurface drainage systems). The right-hand side describes changes in storage due to (*i*) saturation/desaturation of the porous medium (first term) and (*ii*) compressibility of the water and porous medium (second term). For unsaturated flow, the second term is usually neglected, whereas the first term is omitted in groundwater applications. Eq. **1** was solved numerically by using a mass-lumped fully implicit finite difference method with adaptive time stepping (5). The nonlinearities arising from the dependence of K and ψ on water saturation are handled with Newton–Raphson linearization. The MOD-HMS model also was used to simulate transport of seven major ions (7), namely Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}. Solute transport of each aqueous species was simulated by using a finite difference approximation of the 3D advection–dispersion equation (6)

$$\frac{\partial n S_w c_k}{\partial t} = \frac{\partial}{\partial x_i}\left(n S_w D_{ij} \frac{\partial c_k}{\partial x_j} - q_i c_k \right) - \rho_b \frac{\partial \overline{c_k}}{\partial t} - \rho_b \frac{\partial \overline{\overline{c_k}}}{\partial t} - W c_k \quad \forall k = 1,\ldots,7 \text{ , } \mathbf{[2]}$$

where x_i and x_j are Cartesian coordinates [L], with i,j = 1,2,3 corresponding to the three major axes ($x_1 = x$, $x_2 = y$, $x_3 = z$); t is time [T]; c_k is total dissolved concentration of aqueous species k [M/L^3], $\overline{c_k}$ is total sorbed phase concentration of aqueous species k [M/M], $\overline{\overline{c_k}}$ is total solid-phase concentration of aqueous species k [M/M], n is porosity, S_w

is water saturation [–], q_i is water flux along the *i*th axis [L/T], ρ_b is bulk density [M/L^3], D_{ij} is the (*i*, *j*)-th element of the dispersion tensor [L^2/T], and *W* is a water sink term [1/T], passively removing solutes (e.g., agricultural drain, pumping well). For nonreactive species (Cl^- only), the second and third terms on the right side are zero. For all of the other ions, the second and third terms are determined by solving complex salt chemical reactions between the dissolved, adsorbed, and solid phases (5, 7). The reaction system is solved with the UNSATCHEM (8) major ion chemistry modules. The chemical reactions include ion complexation, cation exchange, and precipitation–dissolution reactions. Ion activities in solution depend on the ionic strength of the solution, which is calculated by using the Debye–Huckel model at low ionic strength and the Pitzer model at high ionic strength. The coupling of transport and reactions is done by using an operator splitting approach.

Vertical discretization was finest in the RZ to capture the distribution of root water uptake, and it became coarser with depth. The top seven layers represented the RZ and were each 0.3-m thick. The next seven layers had thicknesses equal to 0.6, 0.6, 1.2, 1.2, 2.4, 2.4, and 4.5 m, respectively. The three bottom layers were of varying thickness depending on the depth to the Corcoran clay, and were as thick as 30 m. Root water uptake was simulated with a linear root distribution that included soil water stress effects on crop evapotranspiration (5, 6). Annual surface water deliveries for each district were obtained from the U.S. Bureau of Reclamation, and annual irrigation water deliveries, consisting of surface and pumped groundwater, to each grid cell were a function of irrigation efficiency that was determined by groundwater table depth (9). Salt concentration of the applied irrigation water was determined from the information in Table 1, while the salt fluxes in or out of the simulated domain were determined from the simulated water fluxes and salt concentration at the domain boundaries (5). Because no 1940 groundwater-level measurements were available, initial conditions were based on a published 1952 water table map (3), and assuming that the soil was at field capacity.

Spatial distribution of initial concentrations for all aqueous, sorbed, and solid species of the seven major ions (Ca, Mg, Na, K, HCO_3, SO_4, and Cl) were estimated from surveyed interpolated 1940 soil salinity values (10), available groundwater data (11), predicted exchangeable sodium percentage (%) using soil survey, and associated cation-exchange-capacity information (4, 5).

Grid-cell-specific soil hydraulic parameters were determined from neural network predictions by using soil texture (5, 12) to represent the hydraulics of the RZ. However, the vertical soil hydraulic conductivity function was linearized to remove nonlinearity of flow, thereby significantly reducing computing time. For the model layers below the RZ, the spatial distribution of the vertical and horizontal saturated hydraulic conductivity values was based on well log data (9). To represent dispersion within each model cell, the longitudinal dispersivity, $\alpha_{L,}$ was set to a large value of 0.8 m, as short-term (within a year) and small-scale (within a model grid cell) water flux variations were not explicitly represented in the model (7). The spatial distribution of CEC in the RZ was based on the western Fresno County soil survey (ref. 4; Fig. 5*D*) and on coarse-textured fractions of the grid cells for the deeper layers. Although spatial and temporal variations in soil temperature and CO_2 concentrations may affect soil salinity, constant values were specified. A summary of model parameter values is presented in Table 2.

Model simulation results were compared with historical observations of water table depths, groundwater pumping, subsurface drainage, and soil and groundwater salinity (5) and are partly summarized in Figs. 6, 7, and 8. Observed long-term changes in the flow dynamics of the coupled vadose zone/groundwater system include a general rise in water table levels, accompanied by a switch from locally pumped groundwater to imported canal water as the main source for irrigation water. The accompanying simulated trends in soil and groundwater salinity generally agreed well with available soil surveys and groundwater sampling information. The general correspondence between simulated and measured relationships between total dissolved solids and individual ion concentrations in shallow groundwater (5, 13) confirmed the significance of the effects of soil chemical processes, including gypsum and calcite precipitation–dissolution and cation exchange and suggested that the soil and water chemistry processes were adequately represented in the model. We note that complex modeling results as presented here cannot be validated (14) but that the correspondence of simulated and measured data confirms that the relevant mechanisms were adequately represented in the model.

Nevertheless, additional research is needed in the following areas. First, the spatial and temporal resolution of the model was limited by computational speed and data availability. As a result, the nonlinear processes of variably saturated flow and reactive transport needed to be averaged over relatively large heterogeneous spatial domains (horizontally and vertically) and time periods (annual boundary conditions). This averaging may lead to significant errors. The effects of a coarse vertical discretization and of annually averaging the upper boundary conditions of irrigation and evapotranspiration on simulated soil salinity were found to be small enough to be ignored in the current study (7). Further, many hydrologic parameters were identified by inverse modeling of observed heads and drainage rates (9). In that sense, the parameter values used are effective at the scales of this study and should be interpreted as such. Care should be taken in transferring these to spatial or temporal scales that are different from the ones used here. As computer power further increases, it will become possible to resolve the hydrologic and chemical processes at ever finer scales in regional long-term modeling studies, although limited data availability may not warrant this approach. This discussion brings us to a second point. The results presented here are for a single parameter set. Given the long-term scope and regional-scale extent of the study, significant uncertainty exists on the values of most parameters. Therefore, a thorough sensitivity analysis is needed to assess the robustness of the simulations and the conclusions derived from them. Such an analysis should synthesize our previous work on the sensitivity of the various salinization processes (7) and the regional flow parameters (9). Finally, the modeling results should be further tested against additional measurements of soil salinity, shallow and deep groundwater salinity, and drainage water salinity. Ideally, an extensive monitoring scheme should be initiated.

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