

Root Zone Moisture Routing and Water Demand Calculations in the Context of Integrated Hydrology

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Abstract: An important issue that integrated hydrologic models (IHMs) for river basins can address is the management of water resources in heavily inhabited and cultivated basins. To address this issue, these models need to simulate water demands and root zone flows in a basin. Irrigation scheduling models (ISMs) have been widely used by professionals to compute farm level water demands and root zone flows. Available ISMs are neither suitable for use at basin scale nor can they be easily linked to IHMs. This paper describes a new model that utilizes methods used by ISMs to compute root zone flows and water demands in river basins and can be linked to IHMs. The model was applied to a basin in California, and the simulated water demands were compared with data compiled for the basin. The differences in the results were attributed to differences in input potential evapotranspiration rates. The paper demonstrates that simulated water demands for rice are very sensitive to saturated soil hydraulic conductivity, whereas demands for other crops are sensitive to the pore size distribution index. DOI: 10.1061/(ASCE)IR.1943-4774.0000306. © 2011 American Society of Civil Engineers.

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Introduction

Root zone and land-surface flow processes are an integral part of the hydrologic cycle. They are dictated by soil, climate, and land cover characteristics that have spatial and temporal variability. In heavily inhabited and cultivated basins, these flow processes are also affected by agricultural and urban water management practices. In such basins, surface and subsurface water resources are generally used conjunctively to meet urban and agricultural water demands. In fact, these demands are generally the driving force of the flow processes in the basin. The resulting root zone and land-surface flow processes in turn affect the stream and groundwater flows through surface runoff into streams and recharge to the groundwater. To plan a conjunctive use of surface and subsurface water to meet urban and agricultural water demands at a basin scale, it is necessary to develop a tool that can integrate with the models for the subsurface and surface flow dynamics. This paper presents a new modeling tool that simulates the root zone and land-surface flows along with the urban and agricultural water demands at basin scale in the context of integrated surface and subsurface hydrology.

Irrigation scheduling models (ISMs) have been widely accepted and used by irrigation professionals to compute the agricultural water demands and to time irrigation events. Given the climatic, soil, and crop properties, ISMs simulate the evolution of the soil moisture in the root zone and the agricultural water requirement that depends on the soil moisture (Kincaid and Heerman 1974; Camp et al. 1988; Smith 1991; George et al. 2000; Orange et al. 2004; Snyder et al. 2004; Raes et al. 2009). Generally, these models include a complex representation of the flow dynamics in the root zone and solve a soil moisture balance equation. Some ISMs can also be used in evaluating the effect of regulated deficit irrigation on crops and in computing leaching requirements (Tayfur et al. 1995; Corwin et al. 2007; Heng et al. 2009).

However, ISMs are generally designed to be used at a single-farm scale for a single crop. To use them at basin scale for multiple crops and diverse land uses, it is necessary to execute them several times for each farm and each crop. Other ISMs that are designed for multiple farms generally do not address the flow processes for non-agricultural land-use types such as urban and native vegetation lands (Smith 1991; George et al. 2000). They also do not address intra-farm water management practices such as the irrigation return flow from upstream farms being reused by downstream farms. Most importantly, ISMs are disconnected from the rest of the hydrologic cycle. Since they have no connection to other hydrologic components, such as groundwater and streams, they assume that the computed water demands are always met regardless of the source (pumping versus stream diversions) and the availability of the irrigation water. The Soil and Water Assessment Tool (SWAT), a conceptual model that is designed to assess the effects of water resources management in large river basins, overcomes the limitations previously mentioned (Arnold and Fohrer 2005). However, it uses its own simplistic groundwater and stream routing routines. Linking it to more complex groundwater and stream flow models can be cumbersome and model dependent (Sophocleous et al. 1999).

The California Department of Water Resources (CADWR) has developed the Integrated Water Flow Model (IWFM), a

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finite-element surface-subsurface hydrologic model that couples the integrated hydrologic modeling approach with a root-zone component that simulates agricultural and urban water demands along with the root-zone flow components at basin scale (Dogrul 2007). IWFM has been applied to simulate the surface and subsurface flow dynamics in California's Central Valley (Brush et al. 2008), and it has been interfaced with CalSim, CADWR's simulation and optimization model (Draper et al. 2004). This paper presents the IWFM demand calculator (IDC), IWFM's root-zone component. IDC has been developed so that it can either be used as a stand-alone ISM at basin scale, or it can be linked to IWFM or other finite-element or finite-difference-type integrated hydrologic models. Although IDC has been developed with its integration into hydrologic models in mind, this paper presents IDC as a stand-alone model.

Computational Framework

IDC is designed to compute irrigation and urban water requirements and to route moisture through the root zone at a computational grid. This computational grid can be a regular grid (finite-difference grid) or an irregular grid (finite-element grid). Grid cells are grouped into subregions that are defined by the user. These subregions may represent different types of boundaries at different spatial scales (e.g., hydrologic regions, water districts, counties), or regions where irrigation and water management data are collected. Although IDC requires a computational grid to be defined, it uses neither the finite-element nor the finite-difference approach to solve the conservation equation for the soil moisture in the root zone. Instead, the computational grid is used to adequately represent the spatial distribution of climatic, soil, and irrigation management properties. It also allows IDC to easily link to other numerical engines that operate on computational grids such as integrated hydrologic models. Easy linking to integrated hydrologic models allows calibration of model parameters (e.g., soil hydraulic conductivity, total porosity, or irrigation efficiency) through the observed field data such as groundwater elevations and stream flow records.

Each grid cell area is divided into native and riparian vegetation, urban, rice, wetland refuge, or a user-specified number of non-ponded agricultural crop lands. Rice lands are further divided into lands in which rice residue is decomposed by flooding, where it is decomposed without any flooding, or where it is not decomposed at all. Refuges are divided into seasonal and permanent refuges. Rice and refuge lands are collectively referred to as ponded-crop lands. Even though refuges are not agricultural crops, the refuge ponds are generally managed in a way that is similar to rice ponds, allowing the simulation methods for rice fields to be used for refuges as well. For this reason, refuges are included in the ponded-crop category in IDC. Nonponded crops are agricultural crops that are not grown in standing water like rice (e.g., alfalfa, corn, tomatoes, citrus fruits). A grid cell can have the area of one or more land-use types set to zero. This tells IDC that those land-use types do not exist in that grid cell and the flow simulation for these land-use types is skipped. IDC allows land use to vary over time for each grid cell; a particular land-use type that does not exist in a grid cell in earlier periods of the simulation can exist in the same cell in later periods, or a certain land-use type can disappear from a cell over time.

IDC computes applied water demands for ponded and non-ponded crops at each grid cell under user-specified climatic and irrigation management settings. Urban water demand is computed based on user-specified time-series population and per capita water usage. Native and riparian vegetations are not irrigated; therefore, applied water demands for these land-use types are not computed.

For all land-use types, precipitation and applied water, if any, is routed through the root zone. Any surface runoff owing to precipitation and irrigation generated at each cell is routed to another grid cell, to a subregion, or outside the model area, as specified by the user. Any surface runoff that is routed to a grid cell or subregion becomes part of the applied water in that cell or subregion.

Soil Moisture Routing

IDC uses a physically based approach to compute the root-zone flow processes. For a particular land-use type at a grid cell, the conservation equation for the soil moisture discretized in time is

$$\theta^{t+1} = \theta^t + \Delta t (P^{t+1} - R_p^{t+1} + A_w^{t+1} - R_f^{t+1} - D_r^{t+1} - D^{t+1} - ET^{t+1}) + \Delta \theta_a^{t+1} \quad (1)$$

and

$$R_f^{t+1} = R_{f,\text{ini}}^{t+1} - U^{t+1} \quad (2)$$

where θ = soil moisture (L); P = rate of precipitation (LT^{-1}); R_p = direct runoff owing to precipitation (LT^{-1}); A_w = applied water (LT^{-1}); $R_{f,\text{ini}}$ = initial agricultural return flow (LT^{-1}); U = reused portion of the initial agricultural return flow (LT^{-1}); R_f = net agricultural return flow after reuse takes place (LT^{-1}); D_r = outflow owing to the drainage of rice and refuge ponds (LT^{-1}); D = deep percolation (LT^{-1}); ET = evapotranspiration (LT^{-1}); $\Delta \theta_a$ = change in soil moisture owing to change in land-use area (L); t = time step index (dimensionless); and Δt = simulation time step length (T). These flow terms are depicted in Fig. 1.

In Eq. (1), θ^{t+1} and θ^t are generally less than the total porosity, θ_T , except for rice and refuge lands where ponding is possible. In these areas, θ can be greater than θ_T , and the difference between the θ and θ_T represents the depth of the pond. Therefore, for rice and refuge areas, θ is not truly the soil moisture; it represents the sum of the soil moisture and the depth of the ponded water.

In the following sections, the simulation of the flow processes illustrated in Fig. 1 will be discussed. For simplicity, time indices t and $t + 1$ are dropped, when appropriate, from the flow notations in the remainder of this paper.

Precipitation, P

Precipitation is time-series input data for each grid cell.

Direct Runoff, R_p

IDC uses a modified version of the Soil Conservation Service (SCS) curve number method (USDA 2004) described by Schroeder et al. (1994)

$$R_p = \frac{1}{\Delta t} \frac{(P\Delta t - 0.2S)}{P\Delta t + 0.8S} \quad (3)$$

$$S = \begin{cases} S_{\max} \left[1 - \frac{2\theta - \theta_f}{2\theta_T - \theta_f} \right] & \text{for } \theta > \frac{\theta_f}{2} \\ S_{\max} & \text{for } \theta \leq \frac{\theta_f}{2} \end{cases} \quad (4)$$

$$S_{\max} = \frac{1,000}{\text{CN}} - 10 \quad (5)$$

where CN = curve number specified for a combination of land-use type, soil type, and management practice (dimensionless); $S_{\max}$ = soil retention parameter for dry antecedent moisture conditions (L); S = soil retention parameter at a given moisture content (L); θ_f = field capacity (L); and θ_T = total porosity (L).

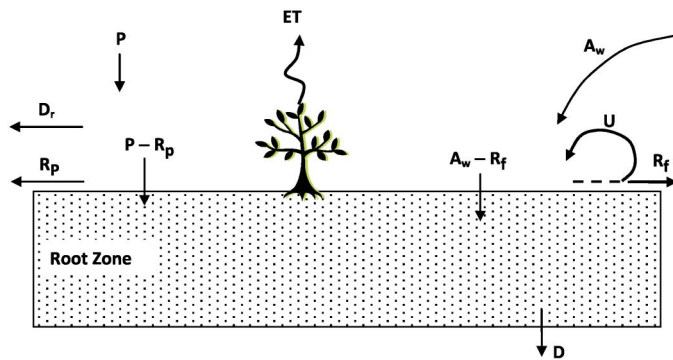


Fig. 1. Schematic representation of root-zone flow terms simulated by IDC

Applied Water, A_w

A_w is either computed dynamically by IDC under user-specified climatic and irrigation management settings or specified directly by the user. In a single simulation, both options can be used; A_w can be computed to meet the demand for some crops and it can be specified for others. Both of these options will be discussed in detail subsequently.

Initial Return Flow, $R_{f,ini}$

Initial return flow is specified by the user as a time-series fraction of the applied water, A_w , for each nonponded agricultural crop and urban land-use area as

$$R_{f,ini} = A_w f_{Rf,ini} \quad (6)$$

where $f_{Rf,ini}$ = initial return flow fraction (dimensionless). For rice and refuge areas, initial return flow is specified by the user as a time-series unit flow rate.

Reuse of Return Flow, U

Reuse of return flow is specified by the user as a time-series fraction of the applied water, A_w , for each nonponded agricultural crop and urban land-use area as

$$U = A_w f_U \quad (7)$$

where f_U = reused return flow fraction (dimensionless). Similar to initial return flow, reuse is specified as a time-series unit flow rate for rice and refuge areas.

U is the reuse that occurs in a single grid cell. In an IDC application, a single grid cell can be large enough to cover several farms. In this case, U represents the total return flow from upstream farms that is captured and reused by the downstream farms in the same grid cell. Another type of reuse occurs when the return flow from a grid cell crosses the cell boundary and flows into a downstream grid cell where it is captured and reused. This type of reuse is not included in U . Instead, it becomes part of the applied water, A_w , for the downstream grid cell.

Net Return Flow, R_f

The net return flow, R_f , is the difference between the initial return flow, $R_{f,ini}$ and the reused return flow, U , as expressed in Eq. (2). Substituting Eqs. (6) and (7) into Eq. (2), R_f can also be represented as

$$R_f = A_w (f_{Rf,ini} - f_U) \quad (8)$$

Eq. (8) is valid for both nonponded agricultural lands and urban areas. It is not used for ponded crops because the initial return flow and reuse are specified explicitly for ponded crops.

Drainage of Rice and Refuge Ponds, D_r

Rice ponds and seasonal refuges are drained during certain periods of the year for harvesting of rice and to convert refuge areas into cultivated farms during growing season. IDC allows the user to simulate such land management practices by requiring time-series ponding depths for rice and refuge areas. Any time the ponding depth specified for a time step is less than that specified for the previous time step, IDC computes a unit rate of pond drainage as

$$D_r^{t+1} = \frac{P_D^t - P_D^{t+1}}{\Delta t} \geq 0 \quad (9)$$

Deep Percolation, D

Deep percolation is the amount of vertical moisture flow that leaves the root zone through its lower boundary. IDC uses a one-dimensional routing approach to compute D . Assuming that the vertical head gradient is unity, using the van Genuchten-Mualem equation (Mualem 1976; van Genuchten 1980) and assuming the residual moisture content is negligible, IDC expresses D as

$$D^{t+1} = K_{sat} \left(\frac{\theta^{t+1}}{\theta_T} \right)^{1/2} \left\{ 1 - \left[1 - \left(\frac{\theta^{t+1}}{\theta_T} \right)^{1/m} \right]^m \right\}^2; \quad (10)$$

$$m = \frac{\lambda}{\lambda + 1}$$

where K_{sat} = saturated hydraulic conductivity (LT^{-1}) and λ = pore size distribution index (dimensionless).

Evapotranspiration, ET

Calculations of ET are based on the potential ET values, ET_{pot} , specified by the user as time-series data for each land use. Although ET_{pot} values can be assumed as the crop ET under standard conditions, ET_c , as described by Allen et al. (1998), they can also be taken as the crop ET under nonstandard conditions, ET_{cadj} , also described by Allen et al. (1998). The exception to this case is if the plants are water stressed because of lack of sufficient water. This situation is simulated dynamically in IDC.

IDC computes ET as a function of the soil moisture in the root zone as

$$ET^{t+1} = \begin{cases} ET_{pot}^{t+1} & \text{if } \theta^{t+1} > \frac{\theta_f}{2} \\ \frac{\theta^{t+1} - \theta_{wp}}{\frac{\theta_f}{2} - \theta_{wp}} ET_{pot}^{t+1} & \text{if } \theta_{wp} < \theta^{t+1} \leq \frac{\theta_f}{2} \\ 0 & \text{if } \theta^{t+1} \leq \theta_{wp} \end{cases} \quad (11)$$

where θ_{wp} = wilting point (L). The method described by Eq. (11) is similar to the method described in Allen et al. (1998) to compute a nonstandard crop ET under water stress conditions with the water stress parameter, p , set to half of field capacity.

Change in Soil Moisture Owing to Change in Land-Use Area, $\Delta\theta_a$

IDC allows the user to specify areas for each land-use type at each grid cell as time-series data. Because of different land-use characteristics and management practices for each land-use, soil moisture will be different for different land-use types. To satisfy the global conservation of mass at the modeled domain, $\Delta\theta_a$ is computed as the term that represents the exchange of soil moisture between different land-use types as their areas change over time. When the area of a particular land use stays the same or decreases, $\Delta\theta_a$ is zero.

When the area of a land use increases, $\Delta\theta_a$ is computed as the total moisture that is assimilated from other land-use types whose areas decrease.

Eq. (1) is nonlinear in reference to θ^{t+1} . IDC uses Newton's method (Gerald and Wheatley 1994) to linearize and solve this equation iteratively at each grid cell for each land-use type.

Water Demand

Physical water demand is the amount of irrigation to satisfy the plant's evapotranspirative requirement under specified irrigation management settings that is not met by precipitation. From a water management perspective, it is the amount of irrigation water that needs to be delivered to farms dictated by contracts. This amount may or may not be the same as the physical water demand of the crops.

IDC is designed to handle both types of water demands under user-specified climatic and irrigation management settings in basin-scale applications. The physical water demand is computed by using Eq. (1), whereas the contractual water demands are specified by the user. Physical water demand is calculated for agricultural crops, refuges, and urban lands. For urban lands, water demand is computed by multiplying the per capita water-use values with the population data, both specified by the user. Water demand is zero for native and riparian vegetation because they are not irrigated.

Water Demand for Nonponded Crops

IDC uses an irrigation-scheduling-type approach in computing the irrigation water demand for nonponded crops. Each nonponded crop is associated with time-series data of irrigation period indicator, irrigation trigger minimum soil moisture, target soil moisture, return flow fraction, and reuse fraction.

The irrigation period indicator represents either the nongrowing period, pre-irrigation period, or the growing period. IDC computes the irrigation water demand only during growing and pre-irrigation periods.

At the beginning of a time step, IDC checks if the soil moisture, θ^t , is less than the irrigation-trigger minimum soil moisture, $\theta_{\min}^{t+1}$, given as a time-series fraction of the field capacity

$$\theta_{\min}^{t+1} = f_{\theta_{\min}}^{t+1} \theta_f \quad (12)$$

where $\theta_{\min}^{t+1}$ may be assumed as the soil moisture that corresponds to the management allowed depletion (Allen et al. 1998). If θ^t is less than $\theta_{\min}^{t+1}$, the irrigation amount to raise the soil moisture up to target moisture, $\theta_{\text{trg}}^{t+1}$, is computed by setting θ^{t+1} in Eq. (1) to $\theta_{\text{trg}}^{t+1}$ and rewriting it for A_w as:

$$A_w^{t+1} = \begin{cases} \frac{\theta_{\text{trg}}^{t+1} - \theta^t - \Delta\theta_a^{t+1}}{\Delta t} - P^{t+1} + R_p^{t+1} + D_{\text{trg}}^{t+1} + \text{ET}_{\text{trg}}^{t+1} & \text{if } \theta^t < \theta_{\min}^{t+1} \\ 0 & \text{if } \theta^t \geq \theta_{\min}^{t+1} \end{cases} \quad (13)$$

Several points need to be highlighted for Eq. (13):

1. Pond drainage flow, D_r , is set to zero because Eq. (13) is written for nonponded crops;
2. $\text{ET}_{\text{trg}}^{t+1}$ and D_{trg}^{t+1} represent the ET and deep percolation rates, respectively, at the target soil moisture, $\theta_{\text{trg}}^{t+1}$;
3. Eq. (8) is used to represent net return flow, R_f ;
4. The inclusion of deep percolation in Eq. (13) shows that the water demand also depends on the soil type where the crops are planted. The same crop under the same management factors and for the same yield will require more water if it was planted on a sandy soil than if it was planted on a clayey soil; and

5. As a stand-alone modeling tool, IDC assumes that applied water is equivalent to irrigation water demand. This assumption is relaxed when IDC is linked to integrated hydrologic models when actual groundwater pumping and stream diversions can be specified through hydrologic simulation. In this case, applied water can be less than irrigation water demand if the aquifer storage and stream flows are depleted, and IDC uses the computed pumping and diversions to meet all or part of the simulated water demands.

Eq. (13) is the expression for the amount of applied water that will raise the soil moisture up to a target level while taking into account the contribution of precipitation, irrigation efficiency measures $f_{R_f, \text{ini}}$ and f_U , and the moisture depleting effects of deep percolation and ET.

By default, IDC uses field capacity as the target soil moisture, $\theta_{\text{trg}}^{t+1}$. However, the user can optionally specify a fraction of the field capacity as the target soil moisture during irrigation to simulate the effects of deficit irrigation (Kirda 2002; Fereres and Soriano 2007). By setting the irrigation-trigger minimum soil moisture and the irrigation-target soil moisture to values that are lower than those for optimal irrigation, the user can simulate the deficit-irrigation practices.

Alternatively, IDC allows the user to specify water demand to address the contractual water demands. This option is useful when it is necessary to model the effects of contractual water demands rather than the physical counterparts. In this case, Eq. (13) is bypassed and user-specified water demands are used. However, it is likely that the specified water demands will be less than or greater than the physical water demands. In either case, IDC uses the specified values in Eq. (1) to route the moisture through the root zone. In the case that the specified demands (therefore, applied water) are less than their physical counterparts, IDC will allow ET to fall below ET_{pot} , assuming that the target irrigation soil moisture is equal to the field capacity. If they are greater than the physical demands, IDC computes increased soil moisture, deep percolation, and return flow, again by using Eq. (1).

Water Demand for Ponded Crops

The water demand computations for ponded crops are driven by the pond depths specified by the user except during decomposition periods for rice lands, in which nonflooded decomposition practices are followed. For the periods when a nonzero ponding depth is specified, IDC computes the applied water demand that will completely saturate the soil and create a pond with the specified depth after taking into account the contribution of precipitation in a user-specified crop management setting. First, an initial estimate of water demand is calculated by setting in Eq. (1) the drainage flow and net return flow to zero, deep percolation to saturated hydraulic conductivity, ET to ET_{pot} , θ^{t+1} to total porosity plus the pond depth, and rearranging the equation for A_w as:

$$A_{w, \text{ini}}^{t+1} = \frac{\theta_T + P_D^{t+1} - \theta^t - \Delta\theta_a^{t+1}}{\Delta t} - P^{t+1} + R_p^{t+1} + K_s + \text{ET}_{\text{pot}}^{t+1} > 0 \quad (14)$$

where $A_{w, \text{ini}}$ = initial estimate of the applied water demand (LT^{-1}) and P_D = pond depth (L). Water demand exists only if the result of Eq. (14) is greater than zero. As the second step, the drainage flow is computed by using Eq. (9). Then, the final applied water demand is computed as

$$A_w^{t+1} = A_{w, \text{ini}}^{t+1} + R_{f, \text{ini}}^{t+1} - U^{t+1} - D_r^{t+1} > 0 \quad (15)$$

where, as previously mentioned, $R_{f, \text{ini}}$ and U are specified as unit flow rates for rice lands and refuges.

Eqs. (14) and (15) are used for seasonal and permanent refuges and for rice lands in which flooded decomposition practices are followed. For rice lands where nonflooded decomposition practices are followed, the same approach is followed during growing season; during the decomposition period, user-specified water application amounts are utilized.

As with nonponded crops, if the user specifies water demands, IDC bypasses its computation and substitutes the specified demand values as applied water into Eq. (1).

Test Case

To demonstrate IDC's performance and the sensitivity of results to some key parameters, it was applied to a section of California's Central Valley (Fig. 2) to simulate the water demands and flow processes over four water years, October 1, 1997, to September 30, 2001. This area was selected because the modeled area intersected with seven detailed analysis units (DAUs; Fig. 3). DAUs are the smallest study areas used by CADWR for analyses of water demand and supply. They are generally defined according to hydrologic features or boundaries of water service agencies. Seasonal applied water and ET values compiled by the CADWR Division of Statewide Integrated Water Management (DSIWM) were also available (CADWR 2009) for these DAUs. In this example, IDC was run with a daily time step utilizing daily precipitation and potential ET rates as input. Although IDC computes flow processes other than applied water, basin-scale data for these flow processes at a daily time step are generally not available. Since this was also the case for this study, only applied water and ET values from IDC were compared to their seasonal counterparts compiled by DSIWM. It was not possible to compare IDC results to real world data because measured water demands and root-zone flow processes are not available at basin scale. Instead, the validation of the methods used in IDC was performed by comparing its results to those from other modeling tools (e.g., DSIWM) considered in

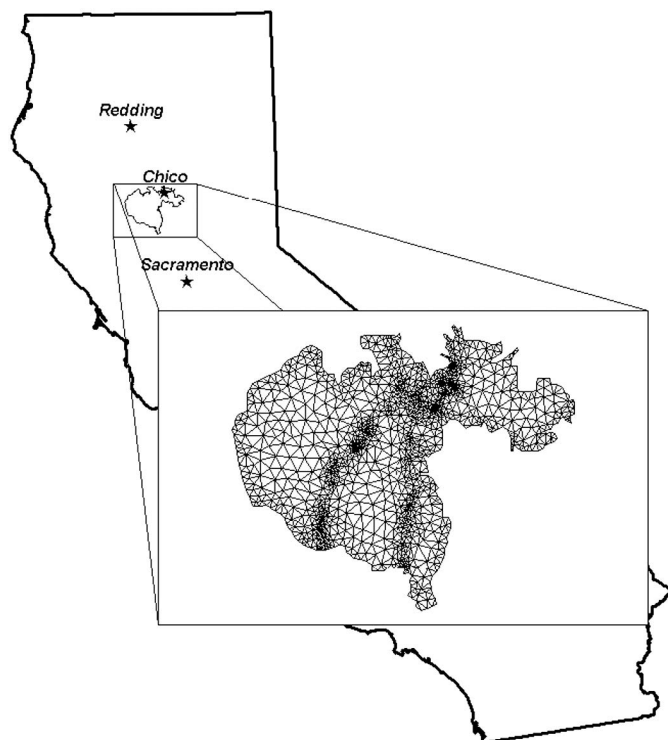


Fig. 2. Model area and the simulation grid for the test case

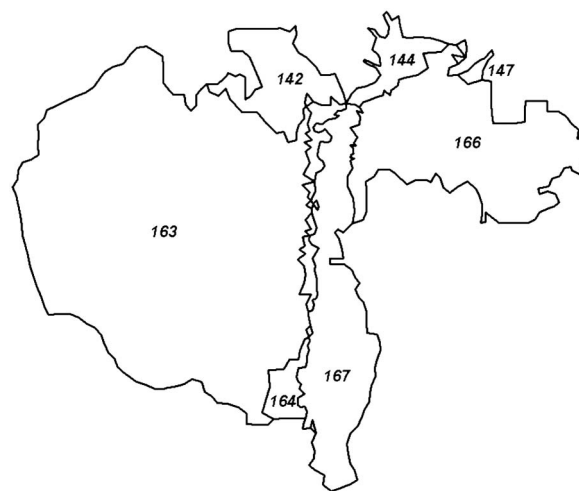


Fig. 3. Model subregions representing the intersection of the model area with the DAUs

this article. Other validation runs can also be found in IDC's theoretical documentation (Dogrul 2009).

The 2,805 km² model area and the finite-element grid with an average cell size of 1.07 km² are shown in Fig. 2. The part of each DAU that intersected with the model area was designated as an individual subregion (Fig. 3), whereas subregions in IDC are used for aggregation and reporting of the simulation results.

The soil properties were compiled from the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic Database (SSURGO). Representative soil properties (e.g., field capacity, total porosity, saturated hydraulic conductivity, and soil hydrologic group) were computed and assigned to each grid cell. The dominant surface soil texture for each grid cell was also identified and the arithmetic mean values for the pore size distribution index listed in Rawls et al. (1982) were assigned to matching soil textures. The wilting point for each cell was set to zero.

Land-use distribution data for water year 1999 for the model area was used for the entire simulation period. In addition to rice fields, 20 non-ponded agricultural crops, including fallow or idle areas, were simulated. The modeled area also included urban areas, wildlife refuges, and native vegetation. The land-use data were intersected with the finite-element grid, and the area of each land-use type over every grid cell was computed.

The simulation time step was a day. Daily precipitation data was available from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate database (PRISM 2009), whereas rice operations and daily potential ET data were available from other CADWR studies.

Results and Discussion

The SSURGO soils database lists upper, lower, and representative values for each soil physical property at every soil horizon. NRCS also provides the Soil Data Viewer that includes several schemes to average horizon-level soil properties to map unit level. By using values from the SSURGO database along with different spatial averaging schemes, it was possible to obtain different values of soil properties and test the sensitivity of IDC results to these properties. Figs. 4 and 5 show the simulated seasonal A_w for nonponded crops at DAU 142 and for rice in DAU 163, respectively, for varying saturated hydraulic conductivities (K_{sat}) averaged over the entire non-ponded crop and rice areas. These DAUs were selected for analysis because DAUs 142 and 163 had the largest percentage of non-ponded crop and rice areas, respectively. Fig. 4 shows

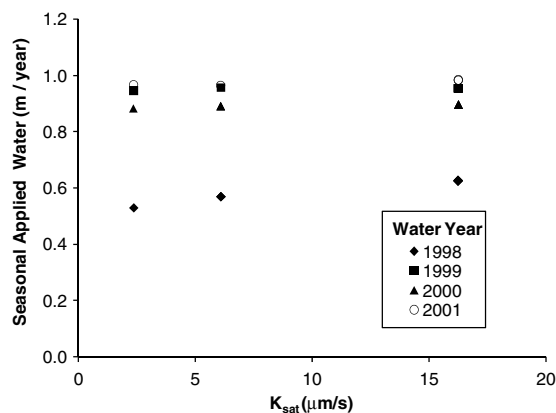


Fig. 4. Seasonal applied water versus saturated hydraulic conductivity for nonponded crops at DAU 142

results for four years, whereas Fig. 5 shows results only for year 2000 because there was no visible difference in the results from one year to another in A_w for rice.

Although A_w for nonponded crops is not extremely sensitive to K_{sat} (Fig. 4), it is very sensitive in the case of rice (Fig. 5). This is expected because rice is grown under saturated conditions and IDC assumes deep percolation is equal in magnitude to K_{sat} at saturation (owing to the assumption of unit gradient). Fig. 5 shows that larger K_{sat} values lead to unreasonably high values of A_w for rice. By using different averaging techniques on upper, lower, and representative K_{sat} values listed in the SSURGO database, the smallest average K_{sat} value obtained was $0.45 \mu\text{m/s}$. By contrast, Williams (2004) reports deep percolation at rice fields between 0.012 to $0.048 \mu\text{m/s}$. Assuming percolation rates reflect K_{sat} values, the smallest value obtained by averaging the SSURGO data is one order of magnitude larger than values reported by Williams (2004) leading to large simulated A_w . Therefore, this example shows that caution needs to be exercised when assigning K_{sat} values to grid elements where rice is grown.

To test how IDC performs for rice fields with soil properties suggested by Williams (2004), grid cells that had rice were assigned K_{sat} values of 0.01 , 0.05 , and $0.1 \mu\text{m/s}$. Under these conditions, A_w for rice computed by IDC for year 2000 was 1.2 , 1.9 , and 2.7 m/year for K_{sat} values of 0.01 , 0.05 , and $0.1 \mu\text{m/s}$, respectively. For comparison, DSIWM reports 1.8 m/year and Williams (2004) reports values ranging from 1.2 – 2.4 m/year . This comparison suggests that IDC is capable of producing reasonable values for A_w at rice fields when grid cell K_{sat} values are set properly.

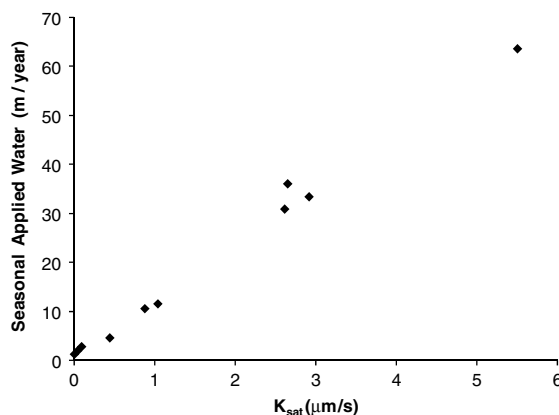


Fig. 5. Seasonal applied water versus saturated hydraulic conductivity for rice at DAU 163 for water year 2000

As previously mentioned, A_w for nonponded crops is not very sensitive to the changes in K_{sat} values (Fig. 4). Fig. 6 shows the seasonal A_w versus pore size distribution index, λ , for DAU 142 at different years. For each soil texture, Rawls et al. (1982) list lower and upper limits along with a representative value for λ . To generate Fig. 6, IDC was run with low, representative, and high values of λ , whereas K_{sat} were set to their representative values from the SSURGO database. To gauge the sensitivity of A_w to K_{sat} and λ values, linear best-fit curves were computed for simulation results shown in Figs. 4 and 6, respectively; a high gradient of the best-fit curve represented high sensitivity. The gradient of the best-fit curve for K_{sat} versus A_w varied from 0.0001 for year 1999 to 0.0062 for year 1998, whereas for λ versus A_w it varied from 0.176 for year 2001 to 0.720 for year 1998. Therefore, A_w for nonponded crops is more sensitive to λ than to K_{sat} .

In summary, K_{sat} values need to be chosen carefully for grid cells where rice is grown. K_{sat} values have minimal effect on A_w for nonponded crops in these cells because they are mostly insensitive to changes in K_{sat} . On the other hand, to modify the A_w for nonponded crops, λ can be modified with no effect on the values computed for rice.

From DSIWM, unit A_w for nonponded agricultural crops and rice and compiled unit ET values were available for each DAU (CADWR 2009). Fig. 7 shows a scatter graph that compares IDC results to those obtained from DSIWM for all DAUs over each year of the simulation period. To produce Fig. 7, daily IDC simulation results were accumulated to annual values because DSIWM results were only available on an annual basis. IDC results are for the case when K_{sat} at grid cells with rice were set to $0.01 \mu\text{m/s}$ and other soil parameters were set to their representative values. The aim of this comparison was not to calibrate IDC to match the values from DSIWM. Instead, DSIWM values were only used as benchmarks to gauge the performance of IDC and to see if IDC produces reasonable values even with no calibration effort.

Fig. 7 shows that annual ET rates for rice are higher in DSIWM than those in IDC, whereas annual ET rates for nonponded crops are lower in DSIWM compared to their IDC counterparts. This suggests that potential ET rates used in producing DSIWM values are different than those used in IDC. Furthermore, precipitation data used by DSIWM in compiling their values was not available. It was also observed that some crops that were present in some sub-regions in IDC had zero acreage in the DSIWM values. The different ET rates, precipitation amount, and crop areas are the potential causes for the differences between the two models.

It is apparent that A_w for nonponded crops is generally higher in IDC (Fig. 7). This can be explained by higher ET rates for

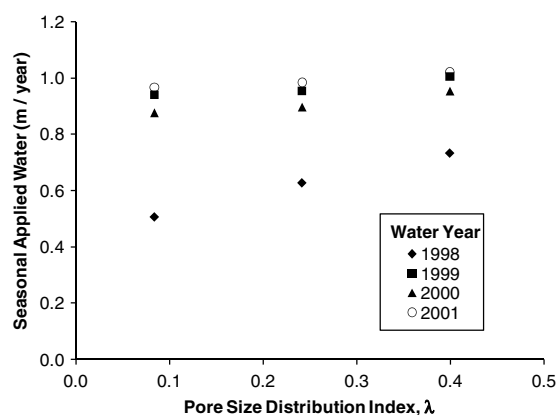


Fig. 6. Seasonal applied water versus pore size distribution index for nonponded crops at DAU 142

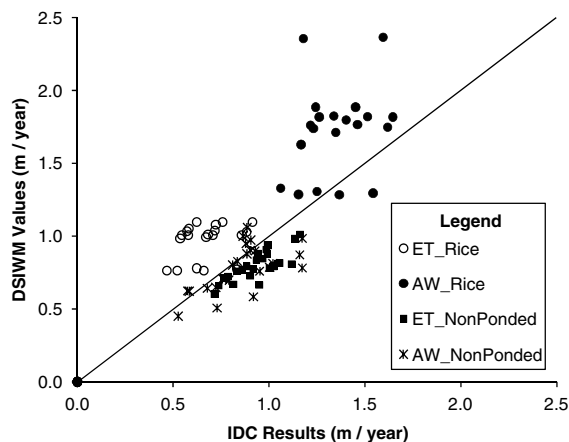


Fig. 7. IDC results versus DSIWM values for all DAUs for the entire simulation period

nonponded crops in IDC than those reported by DSIWM, as shown in Fig. 7. The average annual ET rate for nonponded crops in IDC was 0.14 m higher than those estimated by DSIWM, whereas average A_w rate in IDC was 0.12 m higher than that in DSIWM. For rice, both ET and A_w rates in IDC are less than those reported by DSIWM (Fig. 7). The annual average ET rate for rice in IDC was 0.25 m less than that estimated by DSIWM, whereas average A_w for rice computed by IDC was 0.30 m less than that reported by DSIWM. This analysis shows that most of the differences between A_w computed by IDC and those reported by DSIWM can be attributed to the different potential ET rates used by IDC and DSIWM. Other differences are likely because of different precipitation rates and the infiltration owing to precipitation as computed by IDC and DSIWM. However, precipitation rates were not reported by DSIWM. Fig. 7 also shows a large scatter between A_w for rice computed by IDC and reported by DSIWM. For this example, K_{sat} values at cells with rice were set to $0.01 \mu\text{m/s}$. A better match between A_w for rice computed by IDC and DSIWM can be obtained by modifying the K_{sat} values, particularly when high sensitivity of A_w for rice to K_{sat} values is considered.

A more detailed discussion of this test case can be found in IDC's theoretical documentation (Dogrul 2009). This documentation also includes additional tests on which IDC was used for a hypothetical, single farm with a single crop and the results were compared to the consumptive use program (CUP; Orange et al. 2004), an ISM that was developed jointly by CADWR and the University of California, Davis, to apply ET_c values on a daily basis to determine crop water requirements. The IDC results agreed well with CUP results, showing that methods used by ISMs were implemented correctly in IDC.

Conclusions

This paper introduces the simulation techniques used in IDC, a tool that is designed to route root-zone moisture and compute urban and agricultural water demands at a basin scale. As a test case, root-zone and land-surface flow processes and the agricultural water demands at a section of California's Central Valley have been simulated. It is demonstrated that the water demand for nonponded agricultural crops is sensitive to the pore size distribution index rather than soil saturated hydraulic conductivity, K_{sat} . Conversely, for ponded crops such as rice, the water demand is very sensitive to K_{sat} . Simulated water demands and ET rates are also compared to those obtained from another modeling study. Even with no calibration, IDC produced reasonable values, and the difference between

the results can primarily be explained by the differences in the potential ET rates used by both models. The main strength of IDC is that it can easily be linked to finite-difference or finite-element-type integrated hydrologic models. Although this feature is not presented in this paper, by linking IDC to integrated stream and groundwater flow models one can calibrate root-zone soil and irrigation management parameters by trying to match simulated groundwater levels and stream flows to their measured counterparts. After all, these parameters dictate the recharge into and pumping from groundwater and surface runoff into and diversions from streams. This is a valuable feature because measured groundwater levels and stream flows are widely available compared with flow terms such as deep percolation, agricultural return flow, or direct runoff from precipitation at basin scale.

IDC is an open source computer program. Source code, executables, and a detailed documentation can be downloaded from CADWR's website (Dogrul 2009).

Notation

The following symbols are used in this paper:

- A_w = irrigation water (LT^{-1});
- D = deep percolation (LT^{-1});
- D_r = drainage from rice and wetland refuge ponds (LT^{-1});
- ET = evapotranspiration (LT^{-1});
- K_{sat} = saturated hydraulic conductivity (LT^{-1});
- P = precipitation (LT^{-1});
- R_f = net return flow because of irrigation water (LT^{-1});
- $R_{f,ini}$ = initial return flow before the reuse takes place (LT^{-1});
- R_p = infiltration owing to precipitation (LT^{-1});
- t = time step index (dimensionless);
- U = amount of return flow that is captured and reused in farms (LT^{-1});
- λ = pore size distribution index (dimensionless);
- θ = soil moisture (L); and
- θ_T = total porosity (L).

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