IWFM Demand Calculator:

IDC v4.0

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Theoretical Documentation
and
User's Manual

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1 Introduction

In developed watersheds, the stresses on surface and subsurface water resources are generally created by groundwater pumping and stream flow diversions to satisfy agricultural and urban water requirements. The application of pumping and diversions to meet these requirements also affects the surface and subsurface water system through recharge of the aquifer and surface runoff back into the streams. The agricultural crop water requirement is a function of climate, soil and land surface physical properties as well as land use management practices which are spatially distributed and evolve in time. In almost all integrated hydrologic models pumping and diversions are specified as predefined stresses and are not included in the simulation as an integral and dynamic component of the hydrologic cycle that depend on other hydrologic components as well as water resources operational practices. On the other hand, in irrigation scheduling models that route the moisture through the root zone and compute the irrigation water requirement based on the moisture content, the root zone is completely detached from the rest of the hydrologic cycle. These models generally assume that the water demand is always met and they cannot simulate the effect of extreme hydrologic and operational conditions that may limit the pumping and diversions. Therefore, both integrated hydrologic models and irrigation scheduling models can be coupled to benefit from each other's features. This document discusses a new model developed by the California Department of Water Resources (CADWR) that estimates the irrigation water requirements and route the soil moisture through root zone in the context of integrated hydrologic modeling.

Integrated hydrologic modeling has received much attention in the last few decades. Models such as PRMS (Leavesley et al. 1983), MIKE SHE (DHI 1999), SWATMOD

(Sophocleous et al. 1999), WEHY (Kavvas et al. 2004), GSFLOW (Markstrom et al. 2008), IWFM (Dogrul 2007), HydroGeoSphere (Therrien et al. 2009) and Modflow with Farm Process (Schmid et al. 2009) are developed to route the water through the components of the hydrologic cycle and to simulate the interactions between them. Integrated hydrologic models include the simulation of the land use based runoff processes and the plant consumptive use, and their effects on surface and subsurface flow dynamics. However, except for IWFM, Modflow with Farm Process and SWATMOD, they do not simulate agricultural and urban water demands and the conjunctive use of surface and subsurface water resources to meet these demands. Essentially, they are descriptive models; i.e. given all the stresses on the hydrologic system modeled, they describe where and how fast the water flows.

However, having to pre-specify the stresses such as pumping and stream diversions may pose difficulties in a modeling study. For instance, in the State of California pumping records are proprietary or not measured and often are unavailable. Therefore, for a historical or a calibration model run, the modeler is required to estimate the historical pumping rates to meet an externally computed demand. For instance, Williamson et al. (1989) used electric power records to estimate the historical groundwater pumping in the Central Valley of California. However, such approaches may introduce additional uncertainties to the simulation. On the other hand, in a projection model run where future hydrologic and water resources operational conditions are simulated, pre-specifying pumping and diversions is almost impossible. First, the agricultural and urban water requirements that pumping and diversions are used to meet are not known until after the future conditions are actually simulated. Second, amount of pumping and diversions may be limited by physical (aquifer storage, stream flow capacity, etc.) and contractual limitations which will affect agricultural and urban water requirements, in turn affecting the flow dynamics. This suggests that pumping and diversions in a projection model run are dynamic and depend on other components of hydrologic cycle simulated. They cannot be pre-specified and can only be simulated as an integral part of the evolving hydrologic cycle, and irrigation and urban water requirements that depend on the cycle.

Another type of modeling tool, irrigation-scheduling-type models, treats the root zone component of the hydrologic cycle as detached from other components. Given the climatic, soil and crop properties, these models simulate the evolution of the soil moisture in the root zone and the agricultural water requirement that depends on the soil moisture content (Kincaid and Heerman 1974, Camp et al. 1988, Smith 1991, George et al. 2000, Orang 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 of these models can also be used in evaluating the effect of different farm management scenarios such as regulated deficit irrigation on crops and in computing leaching requirements (Tayfur et al. 1995, Corwin et al. 2007, Heng et al. 2009).

Because of the treatment of the root zone as a component disconnected from the rest of the hydrologic cycle, irrigation-scheduling-type models cannot address situations where applied water is different than the crop irrigation water requirement in a dynamic sense. Similar to the integrated hydrologic models, they require applied water to be pre-defined. The pre-defined applied water can be assumed equal to the crop irrigation requirement, it can be pre-defined as being less than the irrigation requirement to simulate deficit irrigation conditions, or it can be defined to be greater than the irrigation requirement. However, it is not possible to simulate conditions where, throughout the simulation period, aquifer storage or stream flows are depleted such that the pre-defined applied water cannot be met. Another drawback of irrigation-scheduling-type models is that they cannot be calibrated or verified when they are used in regional scale applications. Since they are not connected to the stream network or the underlying aquifer system, it is generally not possible to verify the accuracy of the simulated deep percolation or the simulated surface runoff due to irrigation and precipitation.

In general, the two types of modeling approaches, integrated hydrologic and the irrigation-scheduling-type models, can benefit from each other's capabilities if they are coupled. Integrated hydrologic models need a root zone component that is developed in an irrigation-scheduling-type approach that responds to the hydrologic and farm operational conditions, and compute corresponding water demands. On the other hand, irrigation-scheduling-type models need to be connected to the rest of the hydrologic cycle through coupling with an integrated hydrologic model to receive feedback from the aquifer system and the stream network in terms of simulated pumping and diversions that are actually available.

CADWR has been developing and maintaining the Integrated Water Flow Model (IWFM), a surface-subsurface hydrologic model that couples the integrated hydrologic modeling approach with a root zone component that uses the irrigation-scheduling-type approach (CADWR 2009). Over the years, both IWFM as a whole and its root zone component have evolved to incorporate accurate simulation techniques and to address the issues CADWR have been facing. The root zone simulation engine of IWFM is designed such that it can either be used as a stand-alone irrigation-scheduling-type model or can easily be linked to integrated hydrologic models other than IWFM.

The stand-alone root zone modeling tool is named as IWFM Demand Calculator (IDC). As a stand-alone modeling tool, IDC assumes that the applied water is equal to the computed irrigation water requirements. When IDC's underlying root zone simulation engine is linked to IWFM or any other integrated hydrologic model, applied water is defined as the sum of simulated pumping and stream diversions computed by the integrated hydrologic model. In this case, depending on the state of the aquifer and the stream flows, the applied water can be equal or less than the water demand computed by the root zone simulation engine. The deep percolation, surface runoff due to precipitation and irrigation return flow computed by the root zone simulation engine are passed to the integrated hydrologic model as stresses to the aquifer and the stream network.

This document describes the methods used in IDC (the stand-alone version of the root zone simulation engine) to solve the soil moisture balance in the root zone and to compute agricultural and urban water demands. However, this document should also serve as a guide for the simulation engine when linked to integrated hydrologic models since the methods as well as the input and output data files remain exactly the same.

2 Computational Framework

A computational grid is required when using IDC to compute irrigation water requirements and route moisture through the root zone. This computational grid can be a regular grid (such as a finite difference grid) or an irregular grid (e.g. a finite element grid). However, IDC expects the computational grid to be defined in a manner similar to a finite element grid; i.e. cells and the node numbers that surround each cell should be listed along with the coordinates of the nodes (it should be noted that finite difference grids can easily be defined in this manner). Grid cells are grouped into subregions that are defined by the user. These subregions may represent different types of boundaries and scales (e.g. hydrologic regions, water districts, counties, regions where irrigation and water management data are collected, etc) depending on the requirements of the IDC application. Although IDC requires a computational grid to be defined, it does not use the finite element or the finite difference approach to solve the conservation equation for the soil moisture in the root zone. The reasons for and benefits of using a computational grid are explained later in this section.

Each grid cell area is distributed between native and riparian vegetation, urban, rice, refuge (specifically wetland refuges for waterfowl) and user-specified number of non-ponded agricultural crop lands. Rice lands are further distributed between lands where rice residue is decomposed by flooding (flooded decomp), where it is decomposed without any flooding (non-flooded decomp) and where it is not decomposed at all. Refuges are divided into two groups of 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 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. Non-ponded crops are agricultural crops that are not grown in standing water like rice. The number of non-ponded crops simulated in an IDC application is specified by the user. Therefore, in an IDC application where there are N number of non-ponded crops, the total number of land use types that are simulated at each grid cell will be equal to N+8 (N for non-ponded crops, 5 for ponded crops, 1 for urban, 1 for native vegetation and 1 for riparian vegetation). Even though N+8 land use types are simulated, 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 simulation of these land use types is skipped. IDC allows time series land use areas defined for each grid cell, so a particular land use type that does not exist in a grid cell in earlier times of the simulation period can exist in the same cell in the later times, or an existing land use type can disappear from a cell (this feature allows, for instance, to simulate the effects of agricultural lands and native vegetation areas being converted into urban lands).

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 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 as well as applied water, if any, is routed through the root zone. Any surface runoff due to precipitation and irrigation generated at each cell is routed to a subregion, to another grid cell or to outside the model area, depending on the choice of the user. Any surface runoff that is routed to a subregion or grid cell becomes part of the applied water in that subregion or cell.

IDC is written in Fortran 2003 using an object-oriented programming approach. It consists of i) input data files, ii) output data files, iii) the numerical engine that reads data from input files, computes applied water demands, routes water through the root zone and prints out the results to output files, and iv) a user interface that utilizes an ASCII text file that allows the user to define input and output files and simulation control data for the

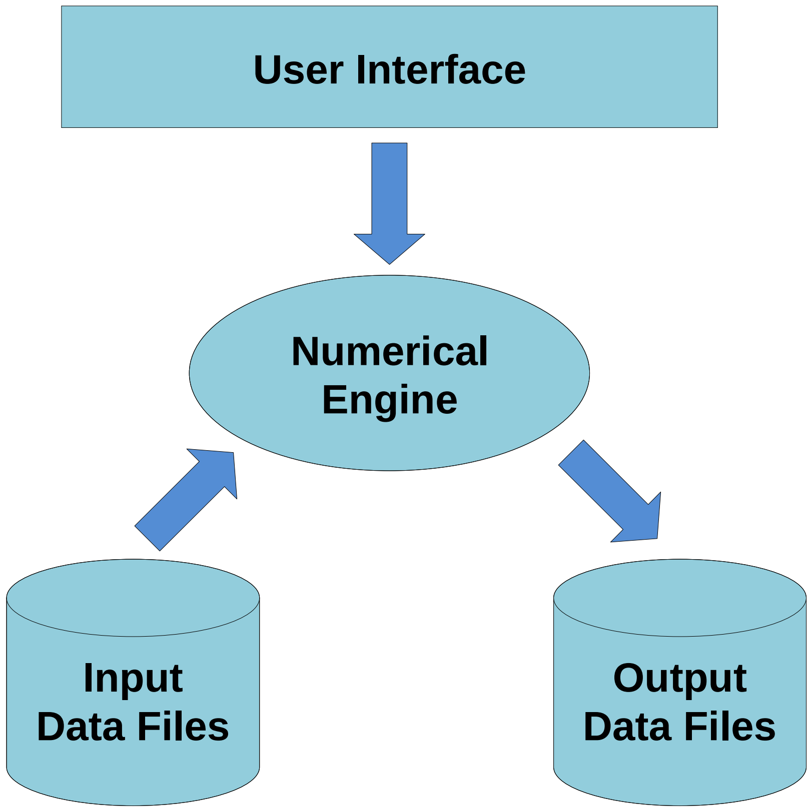


Figure 1. Software components of IDC

numerical engine (Figure 1).

Although IDC does not use finite difference or finite element methods to solve the conservation equation in the root zone, being able to operate on a grid as well as its object-oriented design brings several advantages:

i. The computational grid allows better representation of spatially-distributed data such as potential evapotranspiration, precipitation, soil characteristics, etc.

ii. Being able to operate on computational grids allows IDC to easily couple with other numerical engines that operate on computational grids such as groundwater models.

iii. The object-oriented design allows easy re-compilation of the numerical engine into a dynamic link library (DLL) which allows easy coupling to other hydrologic, biological and environmental numerical engines such as those that comply with Open Modeling Interface (OpenMI) standards (Gregersen et al. 2007, Goodall et al. 2007).

iv. Easy coupling to numerical engines that simulate other components of the hydrologic cycle allows calibration of model parameters (e.g. soil hydraulic conductivity, soil and irrigation management parameters that play a role in the generation of surface runoff, etc.) through the use of widely available observation data (e.g. groundwater elevations and stream flows).

The methods used by IDC to compute water demand and route moisture through root zone at a regional level, and the design of the computational framework make IDC a unique tool.

3 Soil Moisture Routing

Precipitation is generally the natural source for the soil moisture in the root zone. Precipitation that falls on the ground surface infiltrates into the soil at a rate dictated by the type of ground cover, physical characteristics of the soil and the moisture that is already available in the soil. The portion of the precipitation that is in excess of the infiltration rate generates a surface flow. In IDC, this surface flow is termed as *direct runoff*. Irrigation of agricultural lands and urban outdoors such as lawns and parks can also generate surface flows. Surface flows due to irrigation are termed as *return flows* in IDC. Part of the precipitation and irrigation evaporate before infiltrating into the soil. Infiltration due to precipitation and irrigation replenish the soil moisture in the root zone which is also depleted through plant root uptake for transpiration and additional evaporation from the top layers of the soil. The transpiration through the plants and evaporation from the land surface as well as the top layers of the soil are all simulated as a single *evapotranspiration* term in IDC. In general, moisture in the root zone can move in horizontal as well as the vertical directions. In IDC, it is assumed that the horizontal movement of the moisture is negligible compared to the vertical movement. Therefore only the flow of the moisture in the vertical direction is addressed. The moisture that leaves the root zone through its bottom boundary is termed as *deep percolation*.

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

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

and

$$\theta^{t+1} = \theta_P^{t+1} + \theta_{A_w}^{t+1} \quad (2)$$

$$\theta^{t} = \theta_P^{t} + \theta_{A_w}^{t} \quad (3)$$

$$R_f^{t+1} = R_{f,ini}^{t+1} - U^{t+1} \quad (4)$$

where

θ_P = soil moisture content due to precipitation (L/L),

θ_{A_w} = soil moisture content due to applied water (L/L),

θ = total soil moisture content (L/L),

Z = rooting depth (L);

P = rate of precipitation (L/T),

R_P = direct runoff (L/T),

A_w = applied water, i.e. irrigation (L/T),

$R_{f,ini}$ = initial return flow (L/T),

U = re-used portion of the initial return flow (L/T),

R_f = net return flow after re-use takes place (L/T),

D_r = outflow due to the draining of rice and refuge ponds (L/T),

D = deep percolation (L/T),

ET = evapotranspiration (L/T),

$\Delta\theta_a$ = change in soil moisture due to change in land use area (L),

t = the time step index (dimensionless),

Δt = simulation time step length (T).

These flow terms are depicted in Figure 2. The soil moisture in equation (1) is represented as a summation of moisture due to precipitation and applied water in order to keep track of the contribution of applied water to crop evapotranspiration which is termed as ET of applied water (ETaw) by irrigation practitioners.

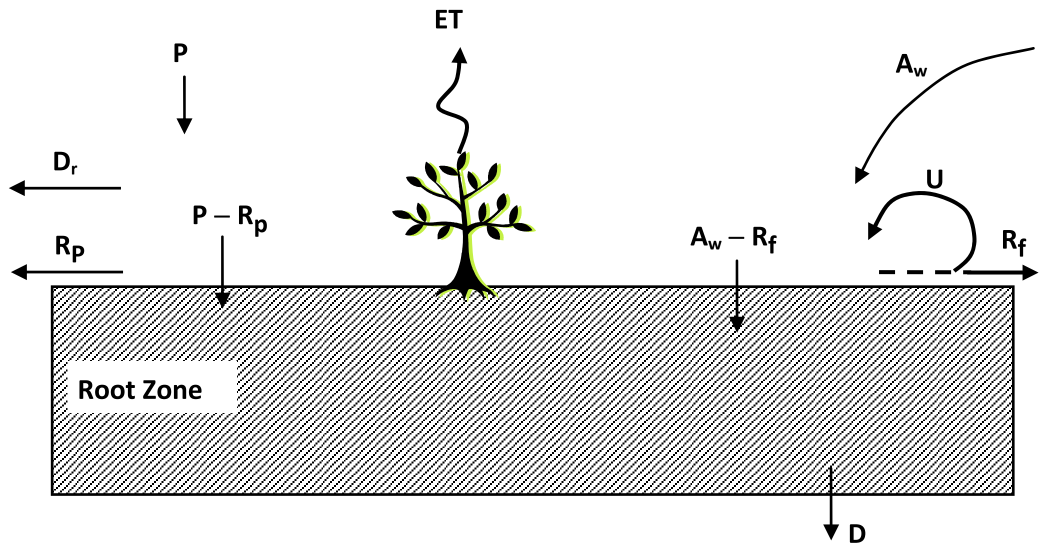


Figure 2. Schematic representation of root zone flow processes simulated by IDC

Equation (1) is solved for each land use type at each grid cell. In equation (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, it is assumed that the rooting depth is constant ($Z^{t+1} = Z^t$), that θ can be computed to 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, θZ is not truly the stored soil moisture in the root zone; 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 Figure 2 will be discussed. For simplicity, time indices t and t+1 are dropped, when appropriate, from the flow notations in the rest of this document.

3.1 Precipitation, P

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

3.2 Direct Runoff, R_P

IDC uses a modified version of SCS curve number (SCS-CN) method (USDA 2004) described by Schroeder at al. (1994):

$$R_p = \frac{1}{\Delta t} \frac{\left(P\Delta t - 0.2S\right)}{P\Delta t + 0.8S} \tag{5}$$

$$S = \begin{cases} S_{max}\left[1 - \dfrac{\theta^t - \dfrac{\theta_f}{2}}{\theta_T - \dfrac{\theta_f}{2}}\right] & \text{for } \theta^t > \dfrac{\theta_f}{2} \\ S_{max} & \text{for } \theta^t \leq \dfrac{\theta_f}{2} \end{cases} \tag{6}$$

$$S_{max} = \frac{1000}{CN} - 10 \tag{7}$$

where CN is the curve number specified for a combination of land use type, soil type and management practice (dimensionless), S_{max} is the soil retention parameter for dry antecedent moisture conditions (L), S is the soil retention parameter at a given moisture content (L), θ_f is the field capacity (L/L) and θ_T is the total porosity (L/L). Equations (5) - (7) state that when root zone moisture is below half of field capacity direct runoff is at a minimum as computed by the SCS-CN method. As the soil moisture increases above half of field capacity the retention capacity of the soil decreases and direct runoff increases.

Equations (5) - (7) are not used for areas such as rice and refuge ponds, and impervious urban areas (parking lots, roof tops, etc) where the infiltration of precipitation is not possible. For these areas entire precipitation becomes direct runoff. For rice lands and seasonal refuges, the ponds are temporary. Therefore, equations (5) - (7) are used during the period when ponds do not exist whereas the entire precipitation is converted into direct runoff during ponding season.

The total direct runoff that leaves a grid cell is the summation of direct runoff from all the agricultural and urban areas at the cell.

3.3 Applied Water, A_w

The main purpose of IDC is to compute dynamically the applied water for agricultural lands that will meet the crop evapotranspirative requirements in climatic and agricultural management settings defined by user-input parameters. The detailed discussion for the computation of applied water is given later in this document. Aside from being able to calculate it, IDC also allows the user to specify applied water. For instance, the amount of applied water may be dictated by contractual agreements rather than the crop evapotranspirative requirements. In a historical simulation, the amount of applied water may be available as historical records whereas in a projection run it will need to be computed. To be able to address such situations, IDC allows the user to specify some or all of the applied water amounts for each agricultural land use at each grid cell as time series input data. Applied water for any agricultural land use that is not assigned user specified values is computed by IDC.

In general, urban applied water to meet municipal and industrial water demand as well as demand for urban outdoors is calculated in terms of rate of water use per capita (e.g. CADWR 2005). For this reason, IDC does not attempt to compute the applied water for urban lands; instead, it is always a user-specified time series input data for urban lands at each grid cell. Urban areas are divided into pervious (lawns, parks and any unpaved outdoor areas) and impervious (roof tops, paved areas such as parking lots) areas. Applied water for urban areas is divided into two parts through user-specified time series fractions to meet the urban outdoors water demand at pervious urban lands, and municipal and industrial water demand at impervious urban lands.

Native and riparian vegetation rely on precipitation alone (the contribution of groundwater to ET of riparian vegetation is not simulated in IDC). Therefore, applied water for these areas is always taken to be zero.

Applied water is computed by IDC or specified by the user for each agricultural and urban land use at each grid cell. It consists of two components: i) surface runoff (combination of return flows due to irrigation, direct runoff due to precipitation, and drainage from rice and refuge ponds) that is generated at an upstream grid cell and used as irrigation water at the grid cell in consideration, and ii) water acquired from other sources such as streams and groundwater (stream flows and groundwater system are not simulated by IDC since IDC only considers the domain that consists of the root zone and the land surface that is separated from the rest of the hydrologic cycle). Another component that can be used to meet the crop evapotranspirative requirements as well as the urban indoors and outdoors water requirements is the re-use of captured return flow, U, in a grid cell (see Figure 2). This component is not included in the definition of the applied water to properly satisfy the statement of conservation of mass. To make a distinction between applied water with and without the re-use component, the applied water without the re-use component, U, is termed as *prime applied water* (i.e. A_w as discussed in this section), and the applied water that includes U is termed as the *total applied water*.

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

Initial return flow is specified by the user as a time series fraction of the prime applied water, A_w, for each non-ponded agricultural crop and urban land use area at each grid cell:

$$R_{f,ini} = A_w f_{R_{f,ini}} \tag{8}$$

where $f_{R_{f,ini}}$ is the initial return flow fraction (dimensionless). For urban lands, the initial return flow fraction only applies to the portion of the applied water that is allocated for the urban outdoors. The applied water that is allocated for urban indoors usage is assumed to become return flow completely.

For rice and refuge areas initial return flow is specified by the user as a time series unit flow rate. Generally, irrigation methods for rice require an additional amount of water to be applied to sustain flow-through type irrigation systems (Williams 2004) where water supplied to the top-most rice field sequentially floods each successive field as it makes its way to the lowermost basin. For refuges, additional water may be necessary to keep the water in the refuge ponds moving to control water quality and algae growth.

For areas with native and riparian vegetation, $R_{f,ini}$ is zero since applied water for these areas is zero.

3.5 Re-use of Return Flow, U

Re-use of return flow is specified by the user as a time series fraction of the prime applied water, A_w, for each non-ponded agricultural crop and urban land use area at each grid cell:

$$U = A_w f_U \tag{9}$$

where f_U is the re-used return flow fraction (dimensionless). Since re-used amount of return flow cannot be larger than the return flow itself, the re-use fraction must be less than or equal to the initial return flow fraction.

Similar to initial return flow, re-use is specified as time series unit flow rate for rice and refuge areas.

U simulates the re-use that occurs in a single grid cell. In an IDC application, a single grid cell can be large enough to cover multiple farms. In this case, U represents the total return flow from upstream farms that is captured and re-used by the downstream farms in the same grid cell. Another type of re-use 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 re-used. This type of re-use is not included in the term U. Instead, as discussed earlier, it becomes part of the prime applied water, A_w, for the downstream grid cell.

3.6 Net Return Flow, R_f

As shown in equation (4), the net return flow, R_f, is the difference between the initial return flow, $R_{f,ini}$ and the re-used return flow, U. Substituting equations (8) and (9) into equation (4), R_f can also be represented as

$$R_f = A_w \left(f_{R_{f,ini}} - f_U \right) \tag{10}$$

Equation (10) is valid for non-ponded agricultural lands as well as urban areas. Equation (10) is not used for ponded crops since re-use and initial return flows are specified explicitly.

The total net return flow that leaves a grid cell is the summation of all return flows from all the agricultural and urban land areas at that cell.

3.7 Drainage of Rice and Refuge Ponds, D_r

Rice ponds and seasonal refuges are drained during certain periods of the year. Rice ponds are drained for harvesting at the end of the growing season. Some rice fields may be re-flooded to decompose the rice residue as well as to create habitat for wildlife. Before the growing season begins, these fields are drained again. Similarly, seasonal refuge ponds can be periodically drained to create space for other types of land usage such as farming 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

$$D_r^{t+1} = \frac{P_D^t - P_D^{t+1}}{\Delta t} \geq 0 \qquad (11)$$

For land use types other than rice and refuges, pond drainage is equal to zero.

3.8 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 physically-based routing approach to compute D:

$$D^{t+1} = K\left(\theta^{t+1} Z^{t+1}\right) \frac{dh\left(\theta^{t+1} Z^{t+1}\right)}{dz} \qquad (12)$$

where K is the unsaturated hydraulic conductivity as a function of soil moisture (L/T), h is the pressure head (L), and z is the vertical distance measured from land surface (L). Assuming that the vertical head gradient is unity, using van Genuchten-Mualem equation

(Mualem 1976, van Genuchten 1980) and assuming residual moisture content is negligible, equation (12) can be re-written as

$$D^{t+1} = D_{rdc}^{t+1} + K_s \left(\frac{\theta^{t+1}}{\theta_T}\right)^{1/2} \left\{1 - \left[1 - \left(\frac{\theta^{t+1}}{\theta_T}\right)^{1/m}\right]^m\right\}^2 \qquad (13)$$

and

$$m = \frac{\lambda}{\lambda + 1} \qquad (14)$$

$$D_{rdc}^{t+1} = \begin{cases} \theta^t \left(Z^t - Z^{t+1}\right) & \text{if} \quad Z^t > Z^{t+1} \\ 0 & \text{otherwise} \end{cases} \qquad (15)$$

where K_s is the saturated hydraulic conductivity (L/T) and λ is the pore size distribution index (dimensionless).

Equation (15) shows that when the rooting depth is decreasing, generally at the harvest time, any moisture that falls outside the rooting depth is converted into deep percolation. However, it should be noted that setting the rooting depth, Z, to zero outside of cropping season will cause incorrect results as IDC will assume that soil has zero storage capacity and will convert all precipitation to either deep percolation or direct runoff. Therefore, it is important to specify a non-zero rooting depth even outside the growing season to properly represent the moisture storage capacity of the soil. Alternatively, one can assume constant rooting depth throughout the entire simulation period. Preliminary tests have shown that although changing rooting depth has an impact on the flow terms as well as the computed water demands at short time periods that are on the order of a few days, over the entire cropping season its cumulative impact is small.

As an alternative to the van Genuchten-Mualem equation, IDC can use Campbell's approach (Campbell 1974) to represent the unsaturated hydraulic conductivity:

$$D^{t+1} = D_{rdc}^{t+1} + K_s \left(\frac{\theta^{t+1}}{\theta_T} \right)^{3+\frac{2}{\lambda}} \tag{16}$$

where the assumption of negligible residual moisture content is applied.

3.9 Evapotranspiration, ET

Calculations of ET are based on the potential ET, ET_{pot}, values specified by the user as time series data for each land use and grid cell combination. Although ET_{pot} values can be taken as the crop ET under standard conditions, ET_c, described by Allen et al. (1998), they can also be taken as the crop ET under non-standard conditions, ET_{cadj}, also described by Allen et al. (1998), to incorporate conditions such as non-uniform irrigation, low soil fertility, salt toxicity, pests, diseases, etc (except the case where the plants are water stressed because of lack of sufficient water; this situation is simulated dynamically in IDC as discussed later).

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

$$ET^{t+1} = \begin{cases} ET_{pot}^{t+1} & \text{if} \quad \dfrac{\theta^{t+1} - \theta_{wp}}{\frac{\theta_f}{2} - \theta_{wp}} > 1 \\[2ex] \dfrac{\theta^{t+1} - \theta_{wp}}{\frac{\theta_f}{2} - \theta_{wp}} ET_{pot}^{t+1} & \text{if} \quad 0 \le \dfrac{\theta^{t+1} - \theta_{wp}}{\frac{\theta_f}{2} - \theta_{wp}} \le 1 \\[2ex] 0 & \text{if} \quad \dfrac{\theta^{t+1} - \theta_{wp}}{\frac{\theta_f}{2} - \theta_{wp}} < 0 \end{cases} \tag{17}$$

where θ_{wp} is the wilting point (L/L). Equation (17) suggests that if the soil moisture at a given time step is greater than half of field capacity, ET will be equal to ET_{pot}. If the soil moisture falls below half of field capacity, plants will start experiencing water stress and ET will be less than ET_{pot}. Below wilting point, the ET rate will be zero. The method described by equation (17) is similar to the method described in Allen et al. (1998) to compute a non-standard crop ET under water stress conditions. In Allen et al. (1998), a water stress parameter, p, is defined for each crop which represents the soil moisture content below which the crop starts experiencing water stress. In equation (17), p is taken as half of field capacity regardless of the plant type.

3.10 Change in Soil Moisture due 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. Equation (1) is solved and soil moisture is tracked for each land use type at each cell. Due to different crop 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, it is necessary to keep track of the soil moisture that is exchanged between different land use types as the areas change through the simulation period. $\Delta\theta_a$ is the term that represents this exchange of soil moisture between different land use types.

As an example consider a total of n land use types defined for a grid cell with corresponding areas defined at time step t and t+1 as A_i^t and A_i^{t+1}, respectively, where i=1,…,n. For land use types whose areas decline or stay the same $\Delta\theta_a$ will be zero (volumetric soil moisture storage will be less for land use types whose areas decrease, but soil moisture depth will be the same for these land use types). On the other hand, land use types whose areas increase will adopt new soil moisture from land use types whose areas diminish. For a land use type j whose area increases by

$$A_j^e = A_j^{t+1} - A_j^t > 0 \qquad (18)$$

the change in soil moisture due to area change, $\Delta\theta_{a,j}$, is computed as

$$\Delta\theta_{a,j} = \frac{A_j^t \theta_j^t Z_j^t + A_j^e \dfrac{\sum_i A_i^r \theta_i^t Z_i^t}{\sum_i A_i^r}}{A_j^{t+1}} - \theta_j^t Z_j^t \qquad (19)$$

where A_i^r is the decrease in the area of land use i:

$$A_i^r = A_i^t - A_i^{t+1} > 0 \qquad (20)$$

Equation (19) suggests that after adopting the soil moisture from land use types whose areas decrease, the new soil moisture computed for the land use j is uniformly distributed over the land use area.

In certain situations, the new soil moisture with the adopted moisture from reduced land use areas can be numerically greater than the total porosity. For instance such a case can occur when the area of a crop with short rooting depth extends into the area of a crop with much deeper rooting depth. In this case the new soil moisture is set to total porosity and the moisture above total porosity is converted into deep percolation.

3.11 Solution of the Root Zone Conservation Equation

Equation (1) is non-linear with respect to θ^{t+1}. IDC uses an iterative method that is a combination of bisection and Newton's methods (Gerald and Wheatley 1994) to solve equation (1). The iterative solution methodology starts and continues with Newton iterations until the estimate for the soil moisture goes above total porosity less 10% of the user-defined convergence tolerance for the iterative solver. At this point, bisection method is used as the iterative method. The reason for this switch between the two methods is that the gradient of the van Genuchten-Mualem equation near saturation becomes very large and this causes problems for Newton's method. Bisection method has slower convergence but is more robust; therefore it is preferred when soil moisture is close to or above saturation. The switch between Newton's and bisection methods occurs mostly for rice and refuge areas where soil moisture can be at or numerically above total porosity (representing the ponding conditions).

4 Water Demand

From a plants perspective, water demand (also referred to as the physical water demand in this document) is the amount of irrigation water to satisfy the crop's evapotranspirative requirement under a specified irrigation management setting 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 contractual agreements. This amount may or may not be the same as the physical water demand of the crops.

IDC is designed to address both types of water demands under user-specified climatic and irrigation management settings in regional scale applications. The physical water demand is computed by utilizing the root zone conservation equation (1), whereas the contractual water demands are specified by the user. Physical water demand is calculated only for agricultural crops, refuges and urban lands; water demand is zero for native and riparian vegetation since they are not irrigated.

Below, the methods used by IDC to compute applied water demand for non-ponded and ponded (rice and refuge lands) land use areas are explained.

4.1 Water Demand for Non-Ponded Crops

IDC utilizes an irrigation-scheduling-type approach in computing the water demand for non-ponded crops. Each non-ponded crop at each grid cell is associated with a time series data of irrigation period flag, irrigation trigger minimum soil moisture, irrigation target soil moisture, minimum deep percolation requirement as a fraction of infiltrated applied water, return flow fraction and re-use fraction. IDC also requires the user to specify if the soil moisture at the beginning or at the end of a time step will be used to compute irrigation water demand. For a short simulation time step such as a day using the soil moisture at the beginning of the time step is appropriate, whereas for a long time step such as a month, it is better to use the soil moisture at the end of the time step. The real-world analogy is that a farmer may check the soil moisture conditions in the morning and decides if the crops need irrigation, while he never bases his decision of irrigating over an entire month on the moisture conditions at the beginning of that month.

The irrigation period flag tells IDC when to compute irrigation water demand for a non-ponded crop. An irrigation period flag of 0 means that it is outside the cropping season and IDC will not compute the irrigation water demand, 1 means that it is growing season and the irrigation water demand as well as ET of applied water (ETaw) and effective precipitation (ETp) will be computed (computation of ETaw and ETp are discussed later), and 2 means that it is a pre-irrigation period when the fields are irrigated as a preparation for crop planting and the irrigation water demand will be computed but ETaw and ETp will not.

First, the water demand calculations in the case when the soil moisture at the beginning of a time step is used will be explained.

At the beginning of a time step, if irrigation period flag is 1 or 2, IDC checks if the soil moisture, $\theta^t Z^t$, is less than the irrigation trigger minimum soil moisture, $\theta_{min}^{t+1} Z^{t+1}$, where θ_{min}^{t+1} is given as time-series fraction of the field capacity:

$$\theta_{min}^{t+1} = f_{\theta min}^{t+1} \theta_f \qquad (21)$$

θ_{min}^{t+1} is the soil moisture content that corresponds to the maximum allowable depletion (Allen et al. 1998). If $\theta^t Z^t$ is less than $\theta_{min}^{t+1} Z^{t+1}$, the irrigation amount to raise the soil moisture up to irrigation target moisture, $\theta_{trg}^{t+1} Z^{t+1}$ is computed by setting θ^{t+1} in equation (1) to θ_{trg}^{t+1} and re-writing it for A_w (in IDC irrigation water demand is equivalent to the applied water since IDC assumes that water is available to meet the irrigation water demand at all times):

$$A_w^{t+1} = \begin{cases} \dfrac{\dfrac{\theta_{trg}^{t+1} Z^{t+1} - \theta^t Z^t - \Delta\theta_a^{t+1}}{\Delta t} - P^{t+1} + R_p^{t+1} + D_{trg}^{t+1} + ET_{trg}^{t+1}}{1 - \left(f_{R_{f,ini}}^{t+1} - f_U^{t+1} \right)} & \text{if} \quad \theta^t Z^t < \theta_{min}^{t+1} Z^{t+1} \\ 0 & \text{if} \quad \theta^t Z^t \geq \theta_{min}^{t+1} Z^{t+1} \end{cases} \qquad (22)$$

Several points need to be highlighted for equation (22):

1. Pond drainage flow, D_r, is set to zero since equation (22) is written for non-ponded crops.
2. ET_{trg}^{t+1} and D_{trg}^{t+1} represent the ET and deep percolation rates, respectively, at the target soil moisture.

3. Equation (10) is substituted for return flow, R_f.

Equation (22) is the expression for the amount of applied water that will raise the soil moisture up to target soil moisture while taking into account the contribution of precipitation, irrigation efficiency measures $f_{R_{f,ini}}$ and f_U as well as the moisture depleting effects of deep percolation and ET.

By default, IDC uses field capacity as the target soil moisture. 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 (Fereres and Soriano, 2007; Kirda, 2002). 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.

In the case where the soil moisture at the end of a time step is used for water demand calculations, IDC initially assumes that A_w^{t+1} is zero, and solves equation (1) for θ^{t+1}. If $\theta^{t+1}Z^{t+1}$ is less than $\theta_{min}^{t+1}Z^{t+1}$, there is a non-zero irrigation water demand and IDC uses equation (22) to compute this demand.

It is common practice to apply additional irrigation water on the fields to flush the salts from the soil. To simulate this practice, IDC allows the user to specify an optional time-series minimum deep percolation factor for each non-ponded crop at each grid cell. The deep percolation factor is defined as a fraction of the infiltrated applied water:

$$D_{min} = f_D\left(A_w - R_f\right) \tag{23}$$

where D_{min} is the minimum deep percolation required (L/T) and f_D is the minimum deep percolation fraction (dimensionless). It should be noted that f_D is different than leaching fraction in that leaching fraction is defined for a set of irrigation events after which the soil salinity and water flow in the root zone reaches an equilibrium (Ayers and Westcot, 1985; Dudley et al., 2008) whereas f_D in IDC is valid only for the time step when the irrigation event takes place.

After water demand is computed using equation (22), IDC checks if deep percolation is greater than the minimum deep percolation, if f_D is supplied. If minimum deep percolation is not achieved, it computes a new water demand that will raise the soil moisture to the irrigation target soil moisture while generating minimum deep percolation. This is achieved by writing equation (23) for $A_w - R_f$, substituting it into equation (1), and solving the resulting non-linear equation for θ^{t+1}:

$$\theta^{t+1}Z^{t+1} = \theta^t Z^t + \Delta t\left[P^{t+1} - R_p^{t+1} - D_{min}^{t+1}\left(1 - \frac{1}{f_D^{t+1}}\right) - ET^{t+1}\right] + \Delta\theta_a^{t+1} \qquad (24)$$

In writing equation (24), pond drainage, D_r, is set to zero since the equation is written for non-ponded crops only and ET^{t+1} is the ET rate at θ^{t+1}. It should also be noted that D_{min} is a function of θ^{t+1} in equation (24).

Equation (24) is solved for θ^{t+1} iteratively using Newton's method. Once the solution is obtained, the water demand is computed as

$$A_w^{t+1} = \frac{D_{min}^{t+1}}{f_D^{t+1}\left[1 - \left(f_{R_{f,ini}}^{t+1} - f_U^{t+1}\right)\right]} \qquad (25)$$

where D_{min}^{t+1} is computed at θ^{t+1} that is obtained by solving equation (24).

Deep percolation has an upper limit that is equal in magnitude to the saturated hydraulic conductivity, K_s, of the soil (see equation (13)). Therefore, D_{min} is limited by K_s. If it is computed to be larger than K_s, it is adjusted down to K_s and the user-specified minimum deep percolation factor, f_D, is overridden.

Alternatively, IDC allows the user to specify water demand to address the contractual rather than the physical water demands. In this case, equations (22) and (25) are 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 equation (1) to route the moisture through the root zone. In the case that the specified demands 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 the use of equation (1).

The inclusion of deep percolation in equation (22) shows that the water demand, among other factors, depends also 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 it was planted on a clayey soil.

4.2 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 where non-flooded decomposition practices are followed. For the periods when a non-zero ponding depth is specified, IDC computes the applied water demand that will completely saturate the soil and crate 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 computed by setting 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 in equation (1) and rearranging the equation for A_w:

$$A_{w,ini}^{t+1} = \frac{\theta_T Z + P_D^{t+1} - \theta^t Z - \Delta\theta_a^{t+1}}{\Delta t} - P^{t+1} + R_p^{t+1} + K_s + ET_{pot}^{t+1} \;\; > \;\; 0 \qquad (26)$$

where $A_{w,ini}$ is the initial estimate of the applied water demand (L/T) and P_D is the pond depth (L). As stated previously, IDC assumes constant rooting depth for ponded crops, therefore the time index for Z in equation (26) does not appear. There is water demand only if the result of equation (26) is greater than zero. As the second step, the drainage flow is computed using equation (11). Then, the final applied water demand is computed as

$$A_w^{t+1} = A_{w,ini}^{t+1} + R_{f,ini}^{t+1} - U^{t+1} - D_r^{t+1} \;\; > \;\; 0 \qquad (27)$$

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

Equations (26) and (27) are used for seasonal and permanent refuge areas as well as for rice lands where flooded decomposition practices are followed. For rice lands where non-flooded decomposition practices are followed, the same approach is used during growing season; during decomposition period user specified water application amounts are utilized.

As with non-ponded crops, if the user specifies water demand IDC bypasses its computation and substitutes the specified value into equation (1).

4.3 Evapotranspiration of Applied Water, ETaw

The portion of the crop evapotranspiration that is satisfied by irrigation water is referred to as the evapotranspiration of applied water (ETaw). The crop evapotranspiration can be satisfied by moisture storage already available in the soil, precipitation and applied water. Moisture storage is comprised of previous precipitation events as well as irrigation activities. Therefore, one can view ETaw as having two components: one where the irrigation satisfies the crop ET requirement almost instantaneously (e.g. over a period of few minutes or hours), and one where a portion of the applied water is stored in the soil and satisfies the crop ET over an extended period of time (e.g. over a period of few days or weeks).

For proper prediction, IDC keeps track of the portion of soil moisture that is supplied by irrigation and effectively simulates both components of ETaw. After equation (1) is solved and all flow components are calculated, ETaw and the soil moisture storage due to irrigation are computed using the following set of expressions:

$$\alpha_{A_w} = \frac{\theta^t_{A_w} Z^t + \Delta t\left(A^{t+1}_w - R^{t+1}_f\right)}{\left(\theta^t_P + \theta^t_{A_w}\right) Z^t + \Delta t\left(P^{t+1} - R^{t+1} + A^{t+1}_w - R^{t+1}_f\right)} \tag{28}$$

$$ETaw^{t+1} = \alpha_{A_w} ET^{t+1} \tag{29}$$

$$\theta^{t+1}_{A_w} Z^{t+1} = \theta^t_{A_w} Z^t + \Delta t\left[A^{t+1}_w - R^{t+1}_f - \alpha_{A_w}\left(D^{t+1}_r + D^{t+1}\right) - ETaw^{t+1}\right] + \Delta\theta^{t+1}_{a,A_w} \tag{30}$$

where α_{A_w} is the ratio of stored applied water plus the infiltrated applied water to the total moisture storage plus total infiltration, and $\Delta\theta_{a,A_w}$ is the moisture storage due to irrigation that is acquired from adjacent land use areas because of change in land use area. Equations

(28) - (30) suggest that all root zone flow components are proportioned between flow due to precipitation and flow due to applied water using the fraction defined in equation (28), which are used to compute the moisture storage due to irrigation.

α_{A_w} represents both the instantaneous and the long-term contributions of irrigation to ETaw and other flow terms. The part with $\Delta t\left(A_w^{t+1} - R_f^{t+1}\right)$ at the numerator represents the instantaneous contribution, whereas the part with $\theta_{A_w}^t Z^t$ represents its contribution that takes place over an extended period of time. Here, the term "instantaneous" refers to any event that takes place over a single simulation time step, Δt.

When irrigation period flag is 0 or 2 representing out-of-growing-season and pre-irrigation periods, respectively, ETaw is computed only to track θ_{A_w} (see equation (30)). However, during these periods it is reported as zero. This is because evapotranspiration may occur outside the irrigation period due to soil evaporation and transpiration from non-agricultural crops such as weeds, whereas ETaw represents the portion of applied water that satisfies the evapotranspirative requirements of only the agricultural crops.

4.4 Effective Precipitation, ETp

Effective precipitation, ETp, is the portion of precipitation that is available to meet crop evapotranspiration. It does not include direct runoff, deep percolation or evaporation before the crop can use it (USDA 1997). Similar to ETaw, ETp represents the instantaneous contribution of precipitation to satisfy the crop evapotranspiration as well as its contribution over an extended period of time. IDC uses the following expressions to compute ETp:

$$\alpha_P = 1 - \alpha_{A_w} = \frac{\theta_P^t Z^t + \Delta t\left(P^{t+1} - R^{t+1}\right)}{\left(\theta_P^t + \theta_{A_w}^t\right) Z^t + \Delta t\left(P^{t+1} - R^{t+1} + A_w^{t+1} - R_f^{t+1}\right)} \tag{31}$$

$$ETp^{t+1} = \alpha_P ET^{t+1} \tag{32}$$

$$\theta_P^{t+1} Z^{t+1} = \theta_P^t Z^t + \Delta t\left[P^{t+1} - R^{t+1} - \alpha_P\left(D_r^{t+1} + D^{t+1}\right) - ETp^{t+1}\right] + \Delta\theta_{a,P}^{t+1} \tag{33}$$

where α_P is the ratio of stored precipitation plus the infiltration of precipitation to the total moisture storage plus the total infiltration, and $\Delta\theta_{a,P}$ is the moisture storage due to precipitation that is acquired from adjacent land use areas because of change in land use area.

Similar to ETaw, ETp is reported only when the irrigation period flag is 1 (i.e. when it is growing season) but θ_P is tracked throughout the entire simulation period.

5 Example 1: Hypothetical Scenario

To test and analyze its results, IDC was run for a hypothetical case where tomatoes were the irrigated crop. Additionally, to test the irrigation scheduling logic built into IDC, it was compared, when applicable, to the CUP model developed jointly by DWR and UC Davis (Orang et al. 2004). CUP is a graphical user interface driven spreadsheet application that was developed to improve the dissemination of crop evapotranspiration (ET_c) information to California growers and water purveyors. The program uses monthly means of solar radiation, maximum and minimum temperature, dew point temperature, wind speed, and daily rainfall data to compute and apply ET_c values on a daily basis to determine crop water requirements.

The testing and analysis of IDC results were performed in several stages. The first stage included a very simple test case with minimum amount of IDC features included. In each consecutive stage another feature of IDC was included in the test and the effects of the feature on the results were analyzed.

For this example, tomatoes were chosen as the crop for which irrigation water requirements were calculated from January 1, 1996 to December 31, 1996. The growing season for tomatoes was April 1 to August 31. For a specified set of weather data, CUP computed daily ET_c values that were input into IDC. Available water holding capacity (the difference between field capacity and wilting point) was 0.14 mm/mm, the rooting depth was set to 1524 mm and the maximum allowable soil moisture depletion was set to 50% of the field capacity. Using soil properties and crop specific information, CUP computed yield threshold depletion and the corresponding allowable moisture depletion (Snyder et al. 2004). The moisture content that corresponded to the allowable soil moisture depletion computed by CUP was input as the irrigation trigger moisture content into IDC. In IDC, the wilting point, field capacity, total porosity and pore size distribution index are taken to be 0.000 mm/mm, 0.270 mm/mm, 0.463 mm/mm and 0.418, respectively. These values were taken from data published by Rawls et al. (1982) for a loam soil. The initial soil moisture content was set equal to field capacity. It was also assumed in IDC that 50% of the initial soil moisture was due to precipitation.

5.1 Zero Precipitation, Deep Percolation and Return Flow

CUP computes runoff due to precipitation differently than IDC. It also doesn't incorporate deep percolation and agricultural return flow into the computation of applied water. To simulate the similar processes, the precipitation in both programs, and saturated hydraulic conductivity and return flow factor in IDC were all set to zero. Figure 3 shows a comparison of IDC and CUP results for this case. In Figure 3, FC is the field capacity, SMmin is the irrigation trigger minimum soil moisture computed by CUP and used as input to IDC, AW_IDC is the applied water computed by IDC, AW_CUP is the applied water computed by CUP, SM_IDC is the soil moisture computed by IDC, SM_CUP is the soil moisture computed by CUP, and ET_c is the crop ET that is computed by CUP and used as input to IDC.

In both models, initial soil moisture is at field capacity. Until April 1, ET_c for bare soil and non-agricultural plants deplete the soil moisture below the irrigation trigger minimum soil moisture. However, since growing season does not start until April 1,

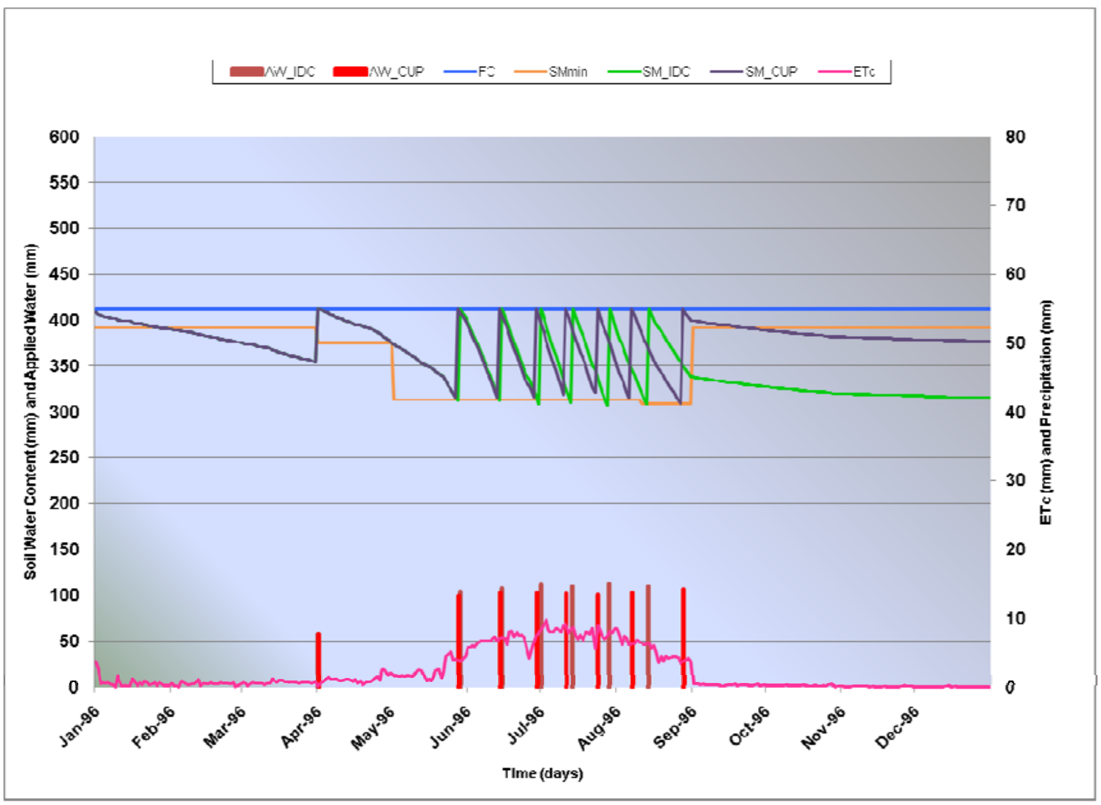


Figure 3. Comparison of IDC results to CUP results for zero precipitation, deep percolation and return flow

irrigation is not triggered. On April 1, when the growing season starts, the first irrigation event is triggered and both models raise the soil moisture up to field capacity. Soil moisture and the magnitude of applied water are almost exactly the same until the second irrigation event towards the end of May. Here, a difference between IDC and CUP becomes apparent. The second irrigation event occurs on May 28 for CUP and on May 29 for IDC. At the beginning of May 28 both models have soil moisture that is above the irrigation trigger minimum soil moisture. CUP predicts that soil moisture at the end of the day will be less than the minimum moisture and initiates an irrigation event. IDC, on the other hand, initiates an irrigation event only based on the soil moisture at the beginning of the day. At the begging of May 29, the soil moisture is less than the minimum moisture in IDC and this is when IDC initiates an irrigation event. The effect of this difference between the two models in deciding when to irrigate accumulates throughout the growing season until the simulated soil moistures are visibly different. In fact, CUP initiates a total of 8 irrigation events that amounts to 774 mm of applied water throughout the growing season whereas IDC initiates 7 events that amounts to 712 mm.

Although there are some differences between IDC and CUP results, in general, this comparison shows that the irrigation scheduling logic built into IDC works properly. IDC allows the depletion of soil moisture until it becomes less than the irrigation trigger moisture. This is when it initiates an irrigation event to raise the moisture up to the target moisture level (field capacity, in this case).

5.2 Zero Deep Percolation and Return Flow

At this stage of testing IDC, daily precipitation data for calendar year 1996 was used. With the inclusion of this data, CUP computed a new set of ET_c and irrigation trigger minimum soil moisture which were used as input to IDC. The results for this stage are shown in Figure 4.

In this stage, another difference between IDC and CUP is shown. CUP never allows the soil moisture to go above field capacity; the infiltration of precipitation is adjusted so that soil moisture stays below or at the field capacity. IDC uses SCS curve number method (USDA 2004) to compute the direct runoff and, consequently, infiltration from precipitation (a curve number of 82 was used for this example). It also allows soil moisture to go above field capacity. This is because past CADWR experiences in coupled root zone, groundwater and stream flow modeling showed that forcing the soil moisture to be at or below field capacity at every time step required increasing direct runoff or deep percolation. This

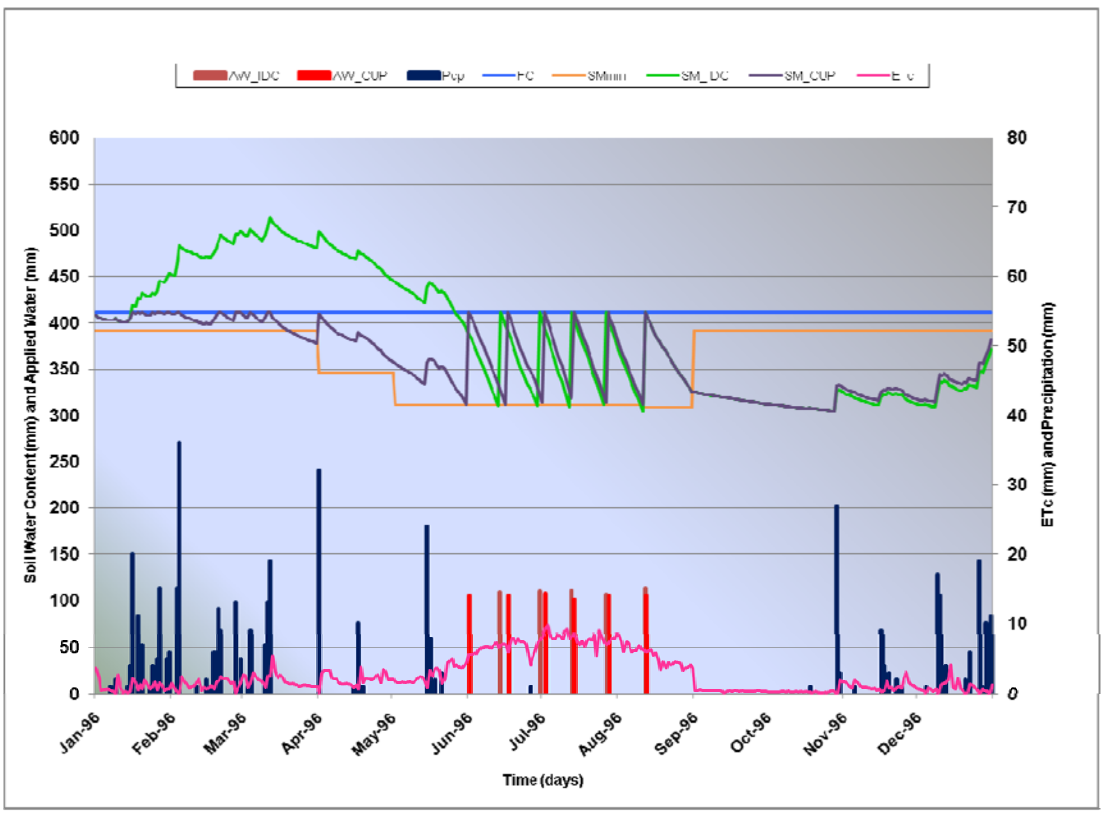


Figure 4. Comparison of IDC results to CUP results for zero deep percolation and return flow

approach had adverse effects on the timing of recharge into groundwater and surface runoff into the streams. Furthermore, it has been observed in the field that considerable root zone drainage can occur beyond three days (Ritchie, 1981) suggesting that the soil moisture stays above field capacity for as long as the drainage continues.

Figure 4 shows that the soil moisture in IDC rises above field capacity with the winter rains whereas CUP limits it with field capacity by decreasing the infiltration of precipitation. For the entire year, IDC and CUP generate 69 mm and 141 mm of direct runoff, respectively, out of 465 mm of precipitation. Although, with different values for curve number, the direct runoff can be changed in IDC, this example shows the effect of allowing the soil moisture to rise above field capacity. With the higher moisture content at the beginning of the growing season, IDC does not initiate an irrigation until June 14, whereas CUP initiates the first irrigation on June 1. For the entire season, the application water for IDC and CUP are 547 mm and 628 mm, respectively.

5.3 Zero Return Flow

At this stage of testing, hydraulic conductivity of the loam soil was set to 1.32 cm/hour (Rawls et al. 1982) to simulate the deep percolation from the root zone. Since deep percolation is not simulated in CUP, the IDC results were compared to the IDC results from previous stage.

Figure 5 shows the results for this test case. The annual deep percolation is 135 mm. When compared to Figure 4, it can be seen that the soil moisture increase during the winter months is less due to the moisture depleting effects of deep percolation.

Inclusion of the deep percolation in the simulation also decreases the direct runoff from precipitation; 57 mm annually in this case versus 69 mm with zero deep percolation.

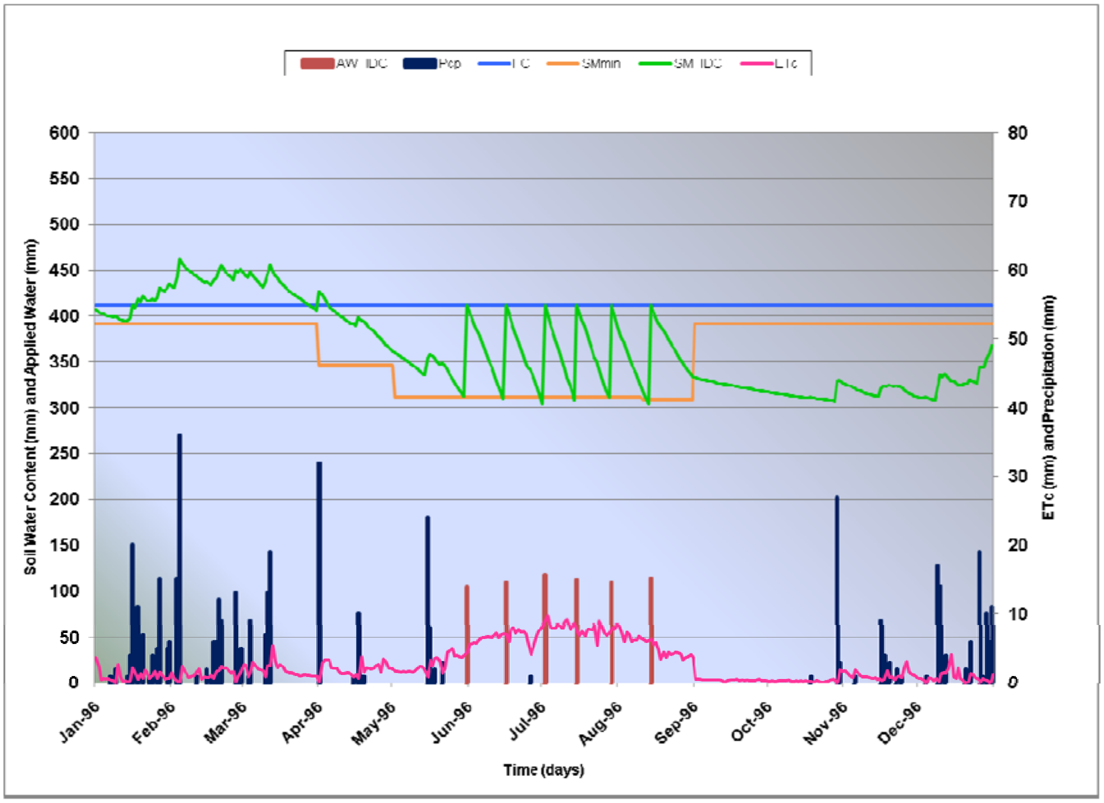


Figure 5. IDC results for zero return flow

This result is expected since depleting the soil moisture through deep percolation leads to increased empty storage to be filled by precipitation.

The annual applied water in this case is 666 mm compared to 547 mm with no deep percolation. This result is also in line with expectations that increasing the deep percolation should also increase the amount of applied water to achieve the same crop yield. In this case, when raising the moisture to field capacity, applied water not only counter-balances the moisture depleting effect of evapotranspiration but also that of deep percolation.

5.4 Zero Return Flow and 1% Minimum Deep Percolation Fraction

In this stage, a minimum deep percolation of 1% of infiltrated applied water is imposed. Figure 6 shows that every time an irrigation event is triggered, the soil moisture is

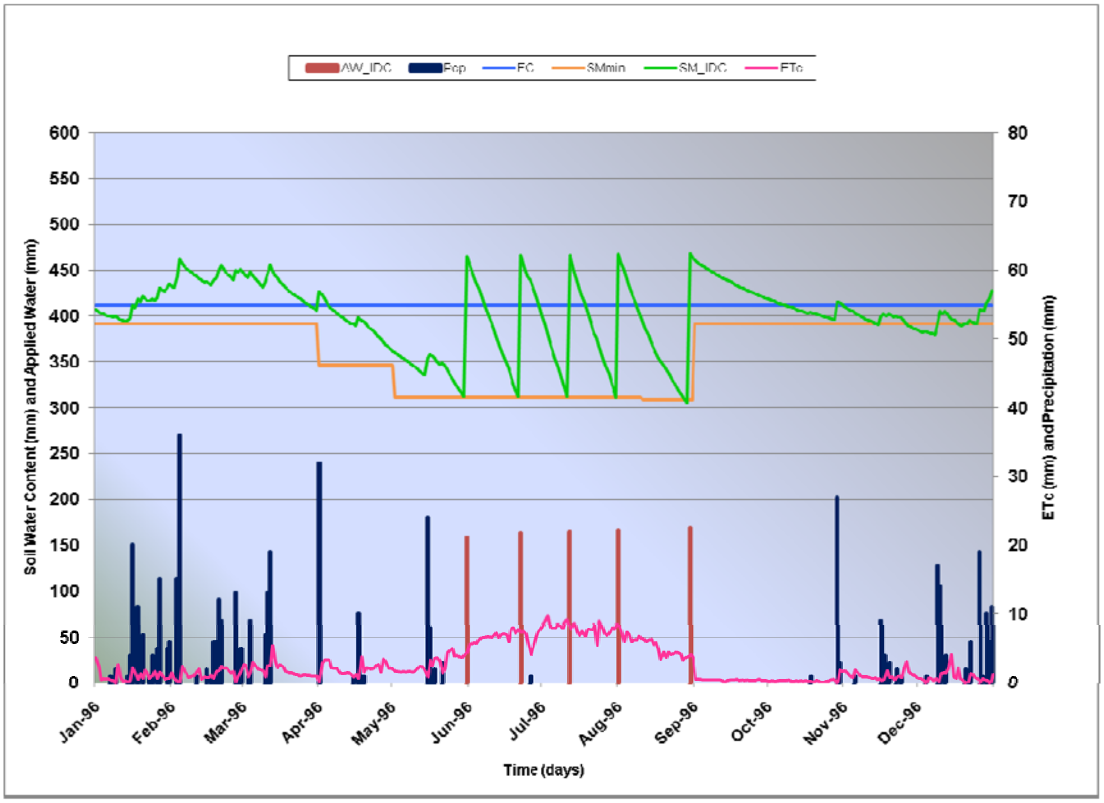


Figure 6. IDC results for zero return flow with 1% minimum deep percolation requirement

raised above field capacity to a moisture that will create a deep percolation that is equal to 1% of the infiltrated applied water on that day. Since the deep percolation continues beyond the day of the irrigation, the total deep percolation from irrigation is larger than 1%. During the growing season, the total deep percolation amounts to 70 mm with 822 mm of applied water. Assuming that the deep percolation is entirely due to irrigation during the growing season, this leads to a leaching fraction of 9%.

5.5 15% Return Flow Fraction

In this case, the minimum deep percolation fraction was set to zero but the return flow fraction was set to 15% of applied water. The results for this case are shown in Figure 7. When compared to Figure 5 of section 5.3 (zero return flow with zero minimum deep

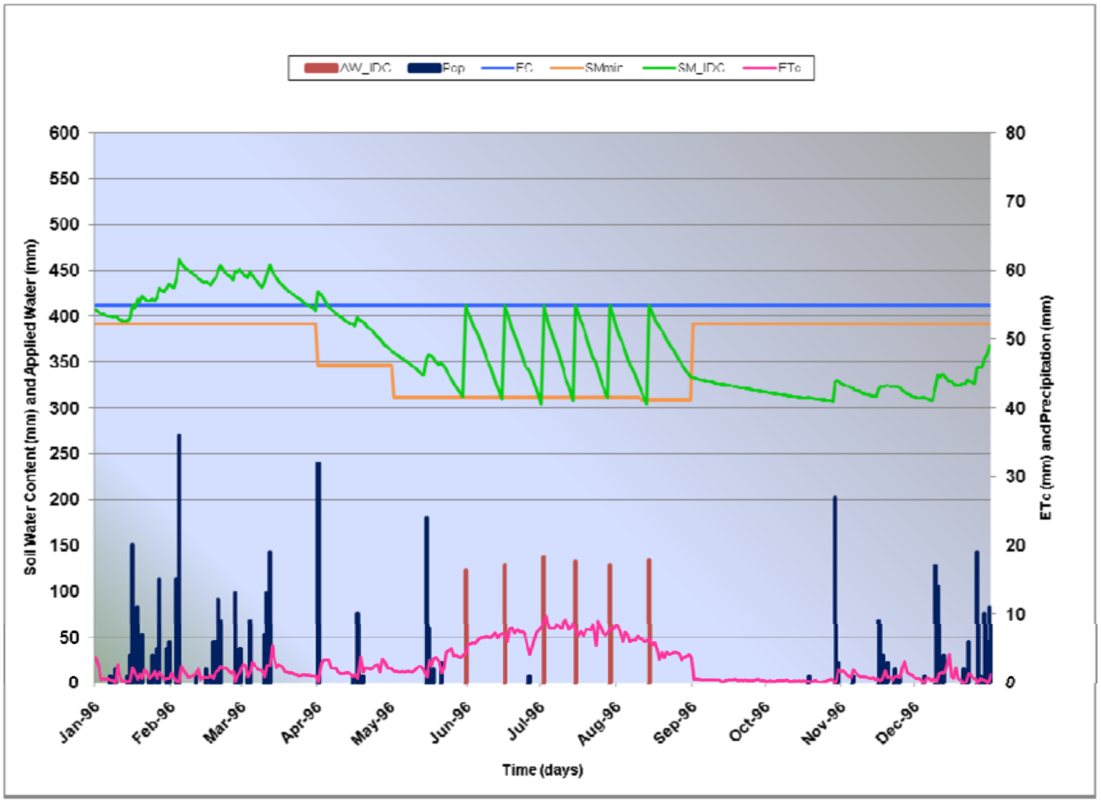


Figure 7. IDC results for 15% return flow

percolation fraction), it can be seen that the only difference is in the amount of applied water. The total applied water in this case was 783 mm compared to 666 mm in the case with zero return flow and minimum deep percolation fraction (see section 5.3). The return flow amount was 117 mm, equal to the difference between the applied water in two test cases. The return flow is taken out of the total applied water and it does not affect the soil moisture dynamics.

5.6 Deficit Irrigation

As a final test case, deficit irrigation conditions were simulated by setting the irrigation target moisture to 60% of field capacity and the irrigation trigger minimum soil moisture to 50% of those used in previous test case (see section 5.5). The results for this case are shown in Figure 8. SMtarget and ET in Figure 8 represent the irrigation target soil moisture and the actual ET, respectively. Deficit irrigation is generally recommended when the losses due to the decrease in the crop yield because of unmet crop ET is surpassed by the gains fromconserving irrigation water (Kirda, 2002). In this test case, the total applied water and crop ET were 594 mm and 718 mm, respectively, compared to 783 mm and 764 mm, respectively, in the non-deficit irrigation scenario simulated in section 5.5. These results show that a 24% reduction in applied water only caused a 6% reduction in the crop ET.

5.7 Additional Comments on Test Cases

Some of the important seasonal (values on the left) and annual (values in parentheses) flow terms from each simulated scenario are listed in Table 1. The scenario simulated in

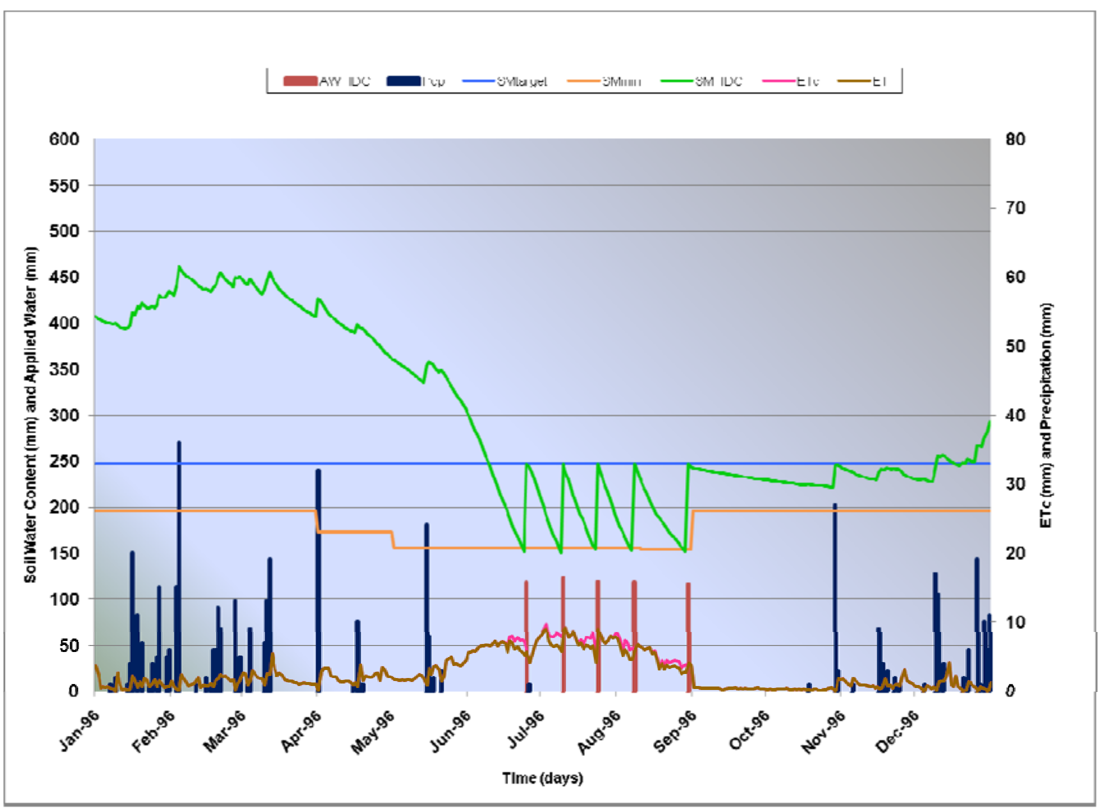


Figure 8. IDC results for deficit irrigation scenario

section 5.1 (zero precipitation, deep percolation and return flow) is not included in the table since the crop ET is different than the other scenarios and it would be difficult to make meaningful comparisons with other scenarios. In Table 1, AW is the applied water, ET is the actual ET, Rp is the direct runoff, Rf is the net return flow, D is the deep percolation, ETaw is the ET of applied water, ETp is the effective precipitation and IE is the irrigation efficiency expressed as ETaw divided by AW.

The following are several comments and conclusions based on the values listed in Table 1:

1. Deep percolation has a direct impact on the irrigation requirement, higher the deep percolation more applied water is needed to meet the crop ET (see AW values for scenarios simulated in sections 5.2, 5.3 and 5.4). However, deep percolation and applied water are not linearly related since a portion of the applied water is stored in the soil.
2. Direct runoff from precipitation decreases as deep percolation increases (see Rp values for sections 5.2 and 5.3). This is because deep percolation depletes the soil

Table 1. Summary of IDC results for the simulated scenarios (values on left are for the growing season, values in parantheses are for the entire calendar year). All values except IE are in mm.

	Scenario				
	5.2	**5.3**	**5.4**	**5.5**	**5.6**
Flow Term	**D=0;Rf=0**	**Rf=0**	**Rf=0;Dmin=1%**	**Rf=15%**	**Deficit Irrig.**
AW	546 (546)	666 (666)	822 (822)	783 (783)	594 (594)
ET	764 (983)	764 (983)	764 (983)	764 (983)	718 (936)
Rp	21 (69)	16 (57)	16 (62)	16 (57)	16 (53)
Rf	0 (0)	0 (0)	0 (0)	117 (117)	89 (89)
D	0 (0)	43 (135)	69 (226)	43 (135)	19 (100)
ETaw	428 (428)	475 (475)	484 (484)	475 (475)	397 (397)
ETp	336 (336)	289 (289)	280 (280)	289 (289)	321 (321)
IE	78%	71%	59%	61%	67%

moisture storage allowing more precipitation to infiltrate. However, as more water is applied to increase the soil moisture above field capacity, increasing the deep percolation for leaching of salts, higher values of direct runoff are observed due to soil moisture being above field capacity at the end of growing season (see Figure 6 and annual Rp values for sections 5.3 and 5.4).

3. Return flow affects the irrigation requirement but not the ET, deep percolation, ETaw and ETp (see relevant flow terms for sections 5.3 and 5.5). As expected, increasing return flow decreases irrigation efficiency.

4. Comparing IE values for sections 5.3 and 5.4, it can be seen that applying more irrigation water for the purposes of leaching decreases the irrigation efficiency. However, an alternative definition of irrigation efficiency includes not only ETaw but also the losses if they are beneficial such as deep percolation for leaching (Burt et al., 1997). Although beneficial deep percolation cannot immediately be quantified through IDC output values, IE would be higher for section 5.4 when the alternative definition of the irrigation efficiency is considered. As a rough estimate, it can be assumed that the difference between the annual deep percolation values from sections 5.3 and 5.4 is the beneficial deep percolation triggered by additional applied water. Then the IE expressed by Burt et al. (1997) can be computed as

$$IE = \frac{ETaw + D_{beneficial}}{AW} = \frac{484 + 226 - 135}{822} \times 100 = 70\% \qquad (34)$$

5. Deficit irrigation is one way of increasing the irrigation efficiency (Kirda, 2002). Table 1 shows a 6% increase in the IE (see IE values for scenarios 5.5 and 5.6) when a deficit irrigation scenario is simulated.

6. IDC uses the ratio of the soil moisture due to irrigation to the total soil moisture storage in computing the ETaw (see equation (29)) and hence the IE. IDC allows the user to input initial soil moisture content due to irrigation and precipitation. The ETaw values at the early stages of the simulation period are largely impacted by the user-defined initial proportioning of the moisture between precipitation and irrigation. Therefore, for a modeling study that addresses a short simulation period such as this example, IE values will be affected by the initial soil moisture estimates. Since the true portioning of the moisture between irrigation and precipitation is hard to estimate, it is advisable to include a "spin-up" period of a few years in IDC runs to achieve a more realistic mixture of stored moisture due to precipitation and applied water. This spin-up period will minimize the adverse effects of incorrect estimates of initial proportioning of the soil moisture storage on the IE calculations.

6 Example 2: A Real-World Application

For this example IDC was used to simulate the irrigation water requirements and root zone flow terms over a period of four water years (October 1, 1997 to September 30, 2001) at a section of California's Central Valley (Figure 9) using field data as input. The reason for the selection of this area was that another project, CalSim 3.0 hydrology development, also addressed the same area. CalSim is the CADWR's model used to simulate California State Water Project (SWP) and the Central Valley Project (CVP) operations. An earlier version of IDC was used during the CalSim 3.0 project so a large portion of the input data for this example was already developed. Furthermore, the modeled area intersected with seven Detailed Analysis Units (DAUs) (Figure 10). DAUs are the smallest study areas used by

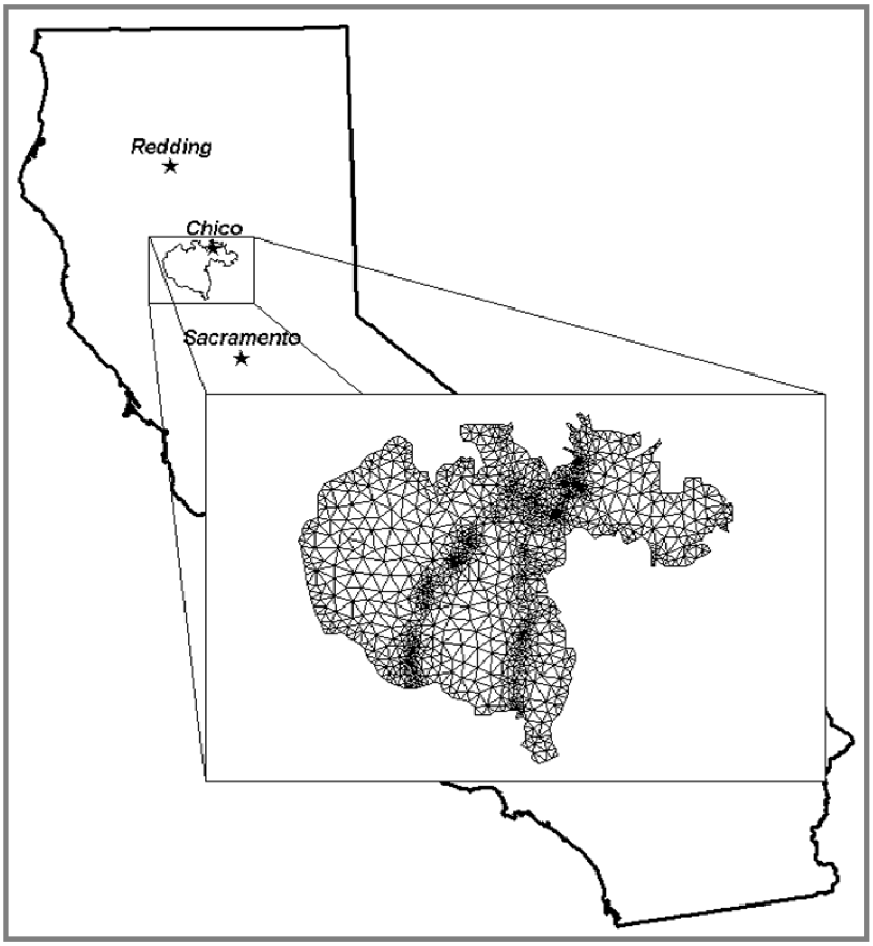


Figure 9. Model area and the simulation grid for Example 2

CADWR for analyses of water demand and supply, generally defined by hydrologic features or boundaries of organized water service agencies. CADWR has collected and developed extensive data sets for these regions. To test their accuracy, IDC results were compared to data developed for the seven DAUs that the model area intersects.

The 2805 km^2 model area and the finite element grid for this example are shown in Figure 9. The simulation grid, which includes 2622 cells, was created using a mesh generator developed by CADWR as an add-on for ESRI's ArcGIS software. The part of each DAU that intersected with the model area was designated as an individual subregion (Figure 10) where subregions in IDC are used for aggregation and reporting of the simulation results.

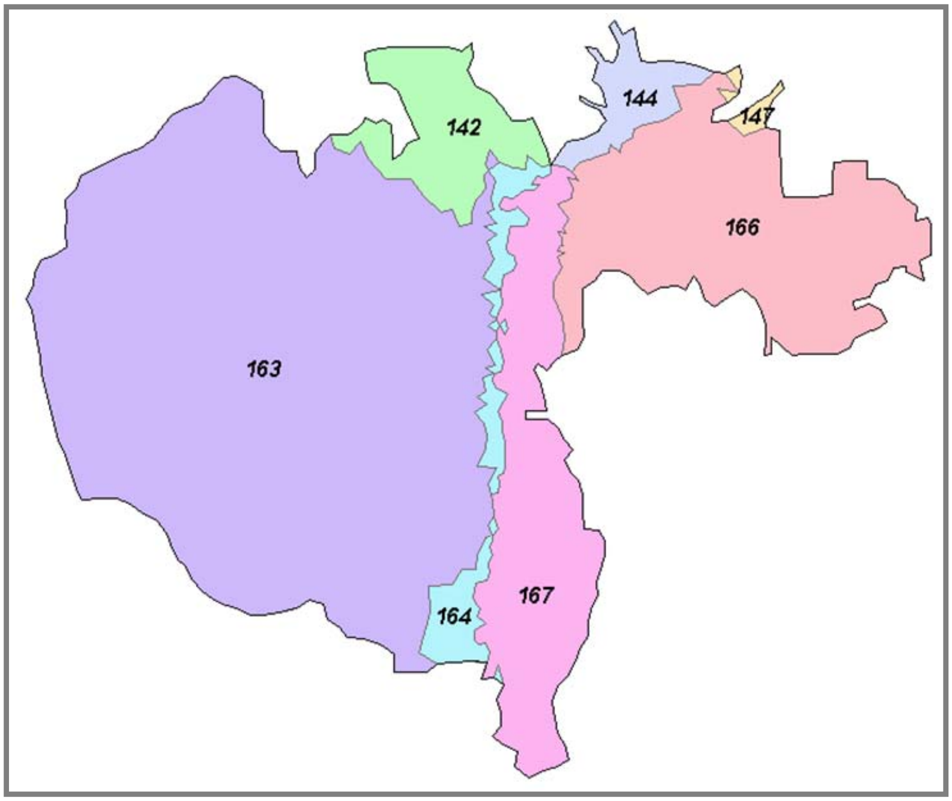


Figure 10. DAUs in modeled area in Example 2

The soil physical properties were compiled using the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic Database (SSURGO). The soils map for the modeled area is shown in Figure 11 without the legend due to highly complex soil structure. Using the Soil Data Viewer software available from NRCS, the soil physical properties (field capacity, total porosity, saturated hydraulic conductivity and soil hydrologic group) were first averaged over soil horizons for each soil component. Properties defined for each component were then averaged for each soil map unit. Finally, properties defined for map units were intersected with simulation grid cells. Since each grid cell intersected with multiple map units, the physical soil properties were further area-averaged over grid cells to end up with a single value for each soil property for each element. The dominant surface soil texture for each grid cell was also identified and the arithmetic mean values for pore size distribution

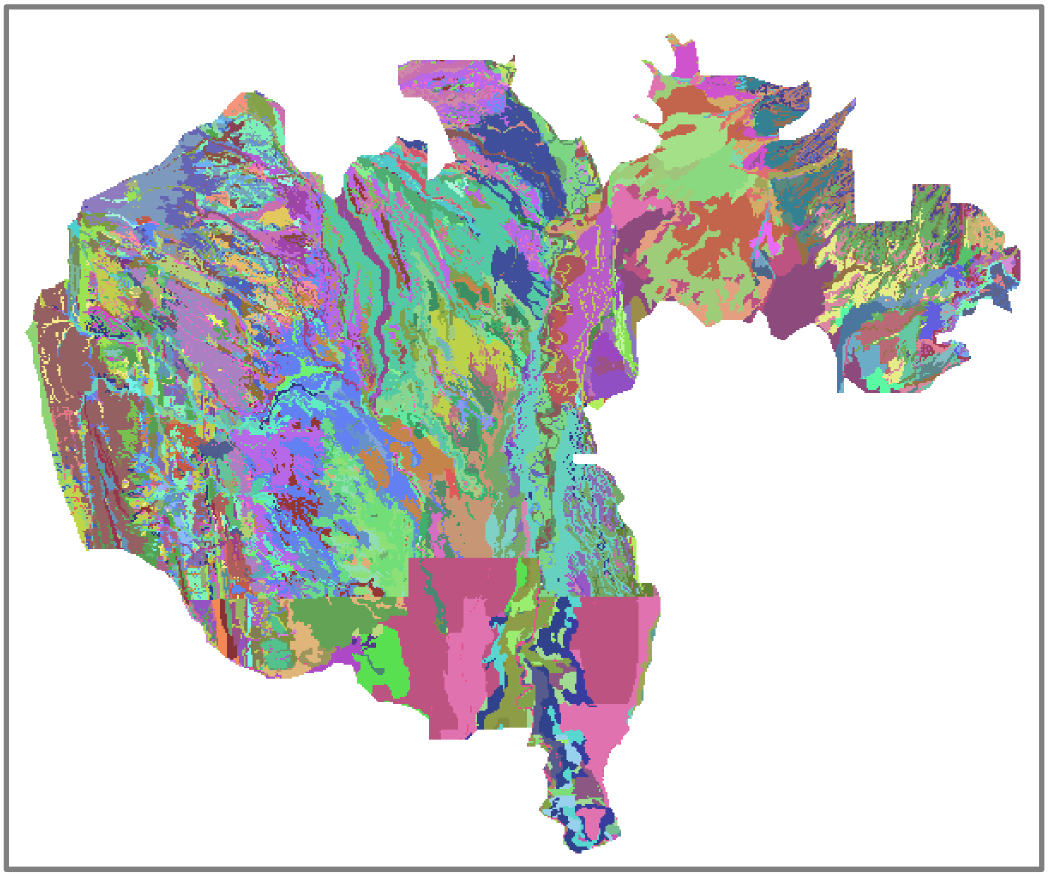


Figure 11. Soils map for the model area

index listed in Rawls et al. (1982) were assigned to matching soil textures. Wilting point for each cell was set to zero.

The land-use map for the model area was available as a Geographic Information System (GIS) layer (Figure 12). The agricultural crops were grouped into 20 non-ponded crop types including fallow or idle areas, and rice fields. The modeled area also included urban areas, wildlife refuges and native vegetation. Total area of water and non-irrigated agricultural lands were minor, 2% and 4% of the total modeled area, respectively. Therefore these land-use types were incorporated into the lands with native vegetation (Figure 12). The land-use map was intersected with the finite element grid and the area of each land-use type over every grid cell was computed.

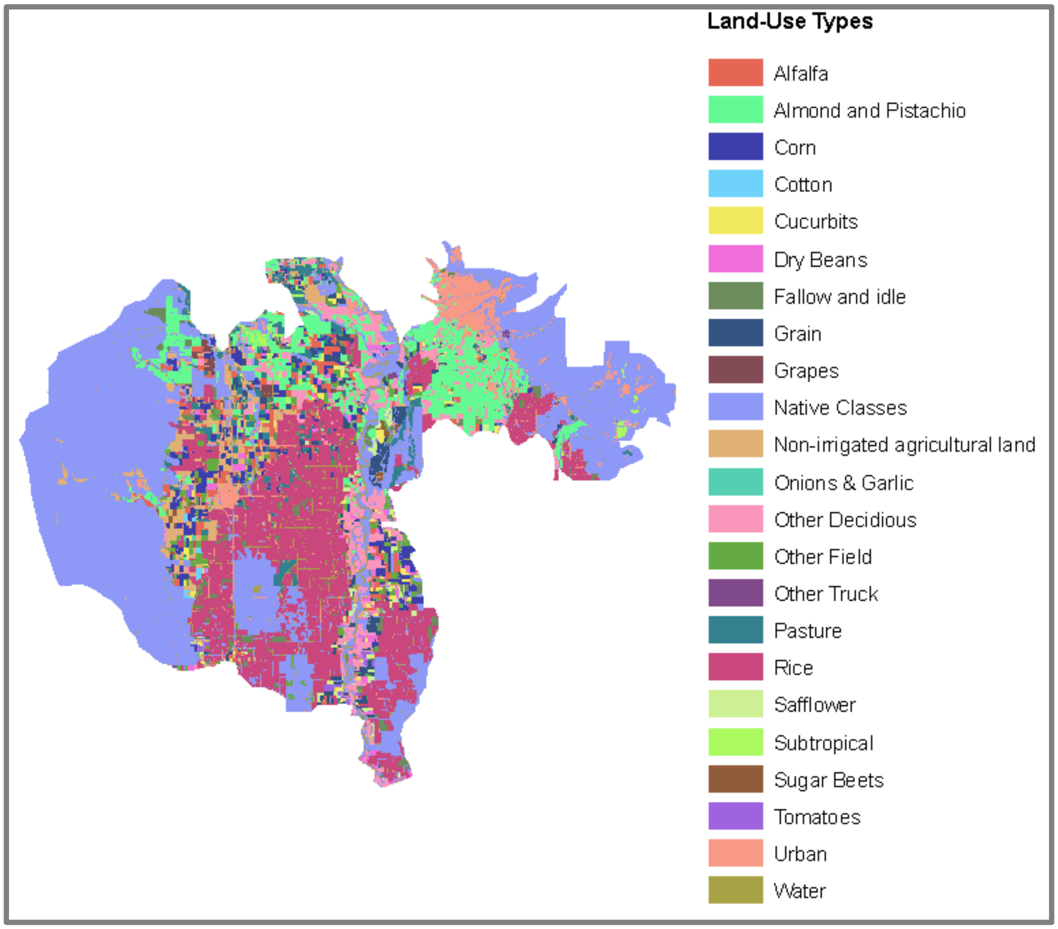


Figure 12. Land-use types in the modeled area

Precipitation data that was developed for Calsim 3.0 project using the PRISM climate data (PRISM, 2009) was utilized in this example.

ET data for each crop at each DAU obtained from DPLA changed from month to another and from year to year. However, it was zero for particular crops when they were not planted in certain years. On the other hand, the land-use areas used in this test was constant and did not change from year to year. Therefore, matching ET data from DPLA with constant land-use areas created a problem: in some years zero ET was assumed for land-use types whose area was not zero. To avoid this problem, ET data for each land use at each grid cell was obtained from the Calsim 3.0 project on a monthly basis. It changed from one month to another but the same monthly values were used for each water year.

Rice operations data such as ponding depths and return flow depths were all taken from Calsim 3.0 study whose source was the Northern District of CADWR.

Even though the irrigation water demand data for modeled DAUs obtained from DPLA was for water years 1998 to 2001, IDC run was started from October 1, 1990; i.e. a spin-up period of eight years was used to ensure that the mixture of soil moisture storage due to irrigation and precipitation was realistic.

6.1 Results and Discussion

The data obtained from DPLA listed crop irrigation requirements for non-ponded agricultural crops and rice as well as ET_c for each DAU as unit rates in terms of acre-feet/acre. To be able to compare to DPLA values, IDC results were also converted to unit rates. Instead of comparing results for individual crops, the total irrigation requirements for each DAU for non-ponded crops computed by IDC were compared to total irrigation requirements for non-ponded crops obtained from DPLA. Irrigation requirement for rice from IDC and DPLA was compared individually since rice irrigation requires much more water than non-ponded crops.

Precipitation is one of the major drivers of the flow processes in IDC. Figure 13 shows the annual precipitation for each DAU.

The Soil Data Viewer from NRCS allows different ways of averaging of the soil physical properties. Also each soil physical property is assigned a lower and upper limit as well as a representative value. Combining the lower, upper and representative values with different averaging methods, one can obtain different values for each soil map unit. Figure 14 and Figure 15 show the simulated irrigation water requirements for non-ponded crops at

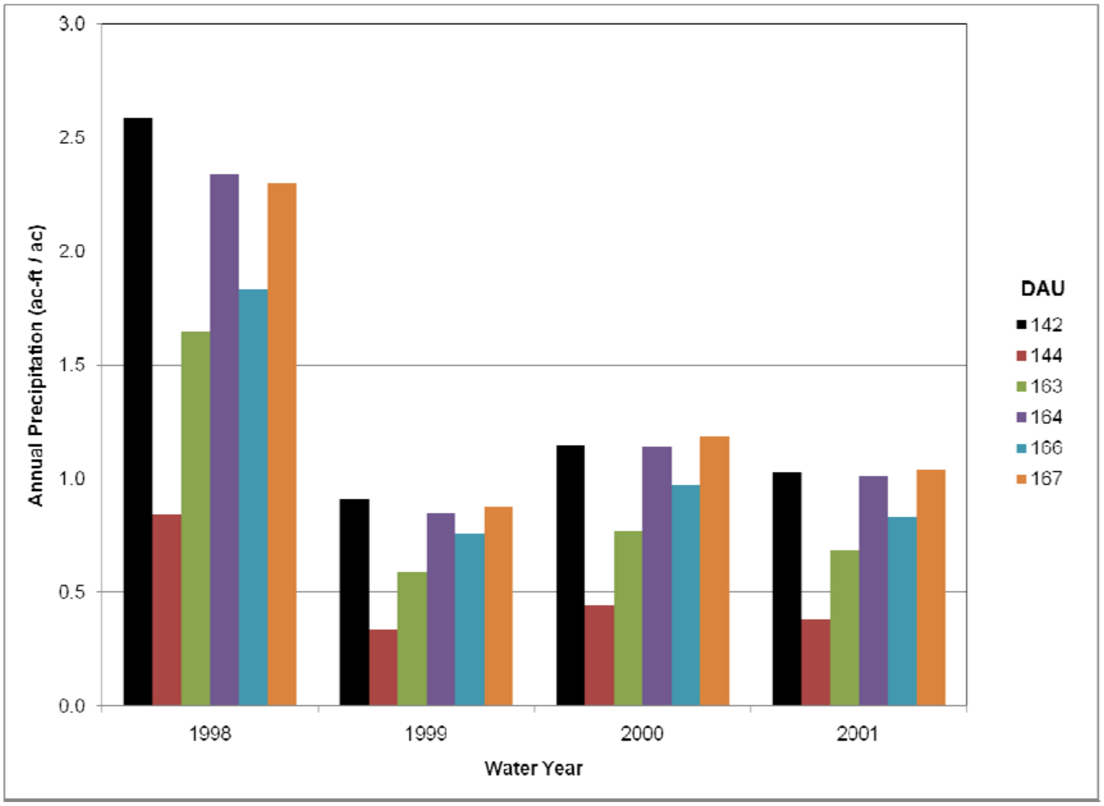


Figure 13. Annual precipitation for each DAU

DAU 142 and for rice in DAU 163, respectively, for varying average saturated hydraulic conductivities (K_{sat}). These DAUs were selected for analysis because DAU 142 had the largest percent non-ponded crop acreage (88% of the total modeled area of the DAU) and DAU 163 had the largest percent rice acreage (24% of the total modeled area of the DAU). Figure 14 shows results for four water years whereas Figure 15 shows those only for water year 2000 because there was no visible difference in the results from one year to another for rice irrigation requirements.

It can be seen that while irrigation water requirement for non-ponded crops is not extremely sensitive to K_{sat} (Figure 14), it is very sensitive in the case of rice (Figure 15). This is expected since rice is grown under saturated conditions. However, even though K_{sat} values shown in Figure 15 were computed using the NRCS data, larger K_{sat} values lead to

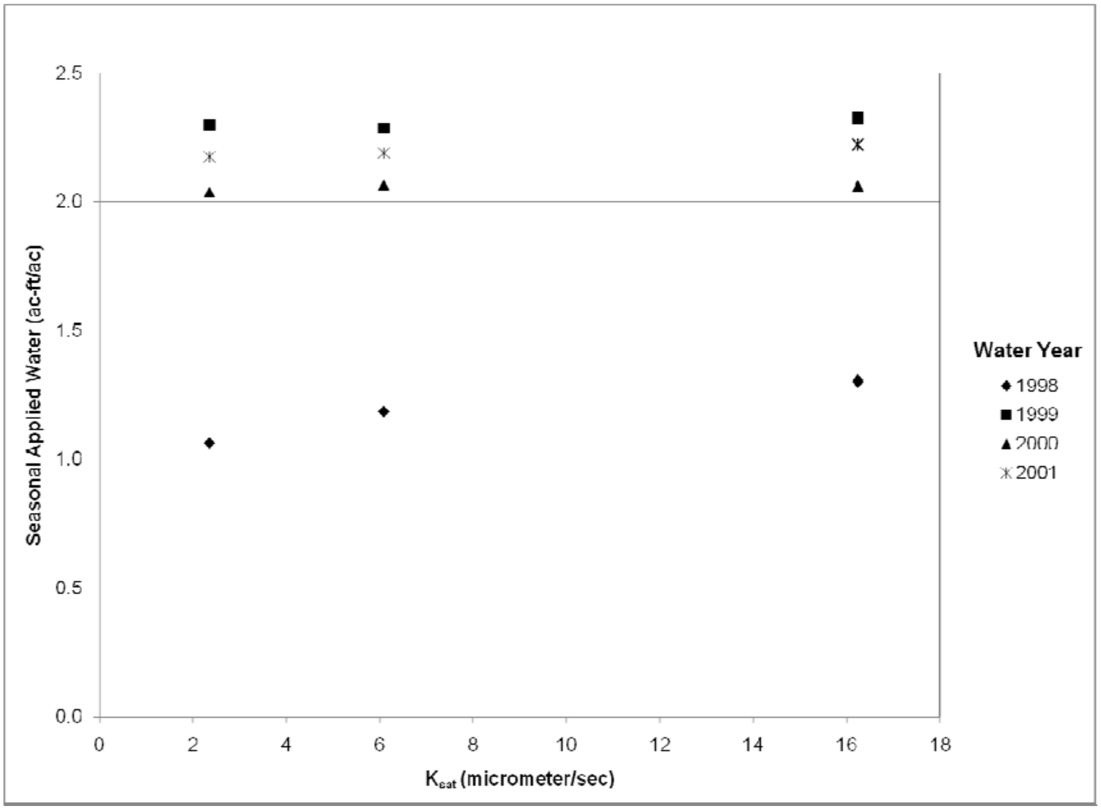


Figure 14. Seasonal irrigation water requirement versus saturated hydraulic conductivity for non-ponded crops at DAU 142

unreasonably high values of irrigation requirements for rice. In fact, using different averaging techniques featured in the NRCS Soil Data Viewer on upper, lower and representative K_{sat} values listed in the SSURGO database, the smallest average K_{sat} value obtained was 0.45 micrometers/sec. By contrast, DPLA assumes an average of 0.01 micrometer/sec (equivalent to 1 inch/month) percolation from rice fields in their analysis. This value is in line with other sources. For instance, Williams (2004) reports deep percolation at rice fields between 0.012 to 0.048 micrometers/sec (1.2 to 4.8 inches/month). Assuming that these rates represent the K_{sat} values, the smallest value obtained by averaging the data from SSURGO is one order of magnitude larger leading to large simulated irrigation requirements for rice. Although a visual inspection of SSURGO data showed that there were

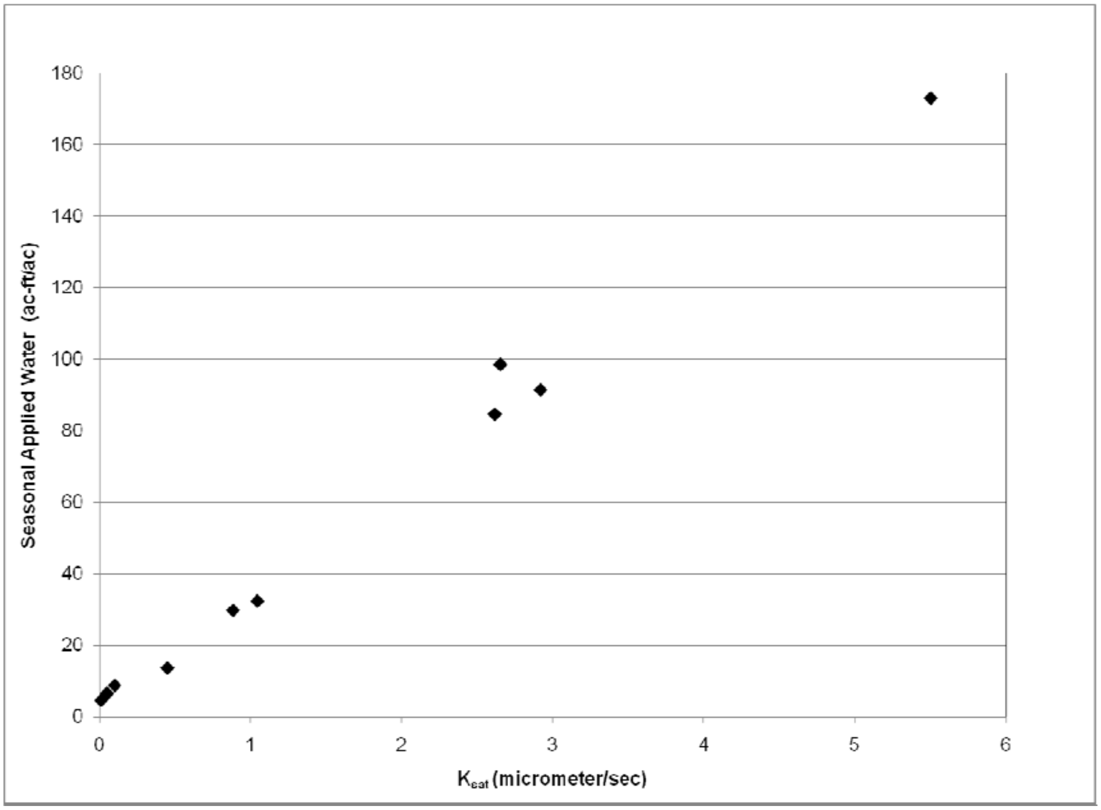


Figure 15. Seasonal irrigation water requirement versus saturated hydraulic conductivity for rice at DAU 163 for water year 2000

K_{sat} values as low as 0.001 micrometers/sec, this example shows that one needs to exercise caution 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 other sources, grid cells that had rice fields were assigned K_{sat} values of 0.01, 0.05 and 0.1 micrometers/sec. The irrigation requirement for rice computed by IDC for water year 2000 was 4.6, 6.4 and 8.7 ac-ft/ac for K_{sat} values of 0.01, 0.05 and 0.1 micrometers/sec, respectively. For comparison purposes, DPLA reports 5.8 ac-ft/ac and Williams (2004) reports an average value of 6 to 6.5 ac-ft/ac which can vary from 4 to 8 ac-ft/ac or more. This comparison suggests that IDC is capable of producing reasonable values for irrigation requirements at rice fields when grid cell K_{sat} values are set properly. In contrast, the rice irrigation requirement computed by IDC with the K_{sat} value at grid cells with rice set to the minimum values obtained by averaging the SSURGO data (0.45 micrometers/sec on average) was 13.6 ac-ft/ac.

As mentioned earlier, irrigation water requirement for non-ponded crops is not very sensitive to the changes in K_{sat} values (Figure 14). Figure 16 shows the seasonal irrigation water requirement (i.e. applied water) versus pore size distribution index, λ, for DAU 142 at different water years. For each soil texture, Rawls et al. (1982) list lower and upper limits as well as a representative value for λ. To generate Figure 16, IDC was run with the K_{sat} values computed by averaging representative values from SSURGO database combined with low, representative and high values of λ listed by Rawls et al. (1982). To gage the sensitivity of

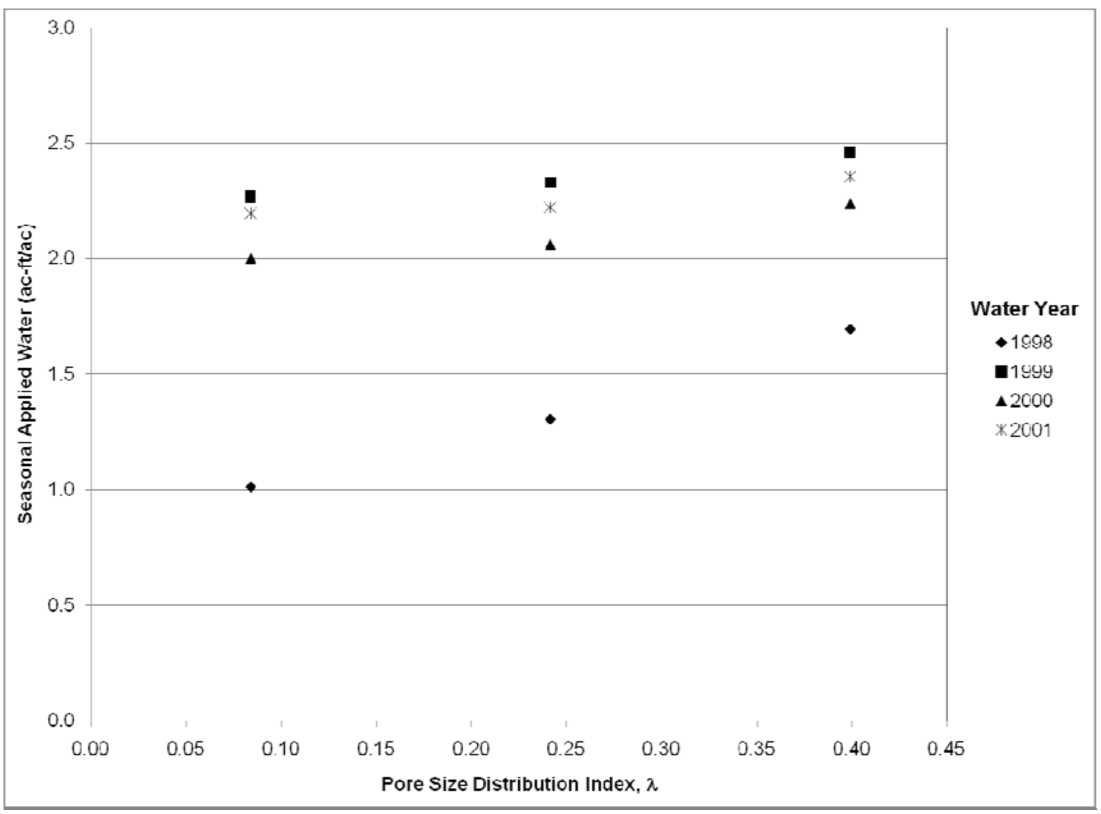


Figure 16. Seasonal irrigation water requirement versus pore size distribution index for non-ponded crops at DAU 142

irrigation requirement to K_{sat} and λ values, linear best-fit curves were computed for simulation results shown in Figure 14 and Figure 16, respectively; high gradient of the best-fit curve represented high sensitivity. The gradient of the best-fit line for K_{sat} versus irrigation requirement varied from 0.0007 for year 2000 to 0.014 for year 1998, whereas for λ versus irrigation requirement it varied from 0.505 for year 2001 to 2.169 for year 1998.

As a summary, one needs to choose K_{sat} values carefully for grid cells where rice is grown. K_{sat} values will not affect the irrigation requirements for non-ponded crops in these cells because they are insensitive to changes in K_{sat} values. On the other hand, to change the irrigation requirement for non-ponded crops one can modify λ with minimal effect on the values computed for rice.

Table 2 shows a general comparison of simulation results for non-ponded crops compared to DPLA values when K_{sat} at grid cells with rice was set to 0.01 micrometers/sec. Deep percolation from DPLA was not available so these values are shown as n/a (not applicable). One can see in Table 2 that the annual ET rates from DPLA change from one year to another, whereas IDC values are constant. This difference is likely to cause other values to be different as well. Furthermore, precipitation data used in DPLA analysis was not available. It was also observed that some crops that were present in some subregions in IDC had zero acreage in DPLA's data. The likelihood of precipitation data being different from IDC data along with different ET rates and different crop areas is responsible for some of the differences among other values such as applied water. Also, ETaw is constantly lower in IDC than in DPLA data, whereas ETp is higher. This means that DPLA values will lead to a higher irrigation efficiency than IDC values. This difference is likely due to different methods used for computing ETaw and ETp as well as different ET and precipitation input

Table 2. Comparison of IDC results for non-ponded crops to the values obtained from DPLA with K_{sat} values at cells with rice set to 0.01 micrometers/sec (all values are in ac-ft/ac; n/a = not applicable)

		ET		AW		ETaw		ETp		D	
Water Year	DAU	IDC	DPLA	IDC	DPLA	IDC	DPLA	IDC	DPLA	IDC	DPLA
1998	142	2.65	2.18	1.74	1.66	1.16	1.24	1.49	0.94	0.63	n/a
	144	2.71	2.68	2.10	1.91	1.23	1.50	1.48	1.17	1.09	n/a
	163	2.34	2.19	1.50	2.04	1.02	1.47	1.32	0.72	0.33	n/a
	164	2.51	2.38	1.20	2.05	0.85	1.52	1.66	0.87	0.40	n/a
	166	2.80	2.54	1.91	2.11	1.13	1.56	1.67	0.98	0.91	n/a
	167	2.01	1.98	1.28	1.47	0.75	1.09	1.26	0.89	0.62	n/a
1999	142	2.65	2.56	2.49	2.57	1.76	1.92	0.89	0.64	0.02	n/a
	144	2.71	2.65	2.78	2.56	1.79	2.01	0.92	0.65	0.12	n/a
	163	2.33	2.49	2.26	3.28	1.55	2.04	0.78	0.45	0.02	n/a
	164	2.50	2.74	2.26	3.47	1.50	2.19	1.00	0.55	0.01	n/a
	166	2.80	2.88	2.56	3.11	1.65	2.29	1.15	0.59	0.16	n/a
	167	2.01	2.17	1.89	2.32	1.15	1.56	0.86	0.60	0.06	n/a
2000	142	2.65	2.60	2.28	2.49	1.64	1.87	1.00	0.74	0.07	n/a
	144	2.71	3.22	2.52	2.86	1.65	2.26	1.07	0.96	0.27	n/a
	163	2.33	2.53	2.07	2.63	1.44	1.92	0.90	0.61	0.04	n/a
	164	2.51	2.77	1.93	2.71	1.36	2.00	1.14	0.76	0.02	n/a
	166	2.80	2.97	2.30	2.96	1.57	2.24	1.23	0.74	0.29	n/a
	167	2.01	2.33	1.63	2.13	1.04	1.57	0.97	0.76	0.11	n/a
2001	142	2.65	2.67	2.42	2.66	1.76	2.01	0.89	0.66	0.05	n/a
	144	2.71	3.32	2.68	3.23	1.75	2.53	0.96	0.79	0.20	n/a
	163	2.33	2.60	2.17	2.88	1.55	2.10	0.78	0.50	0.03	n/a
	164	2.51	2.88	2.09	2.95	1.50	2.20	1.01	0.68	0.01	n/a
	166	2.80	3.08	2.61	3.19	1.66	2.40	1.14	0.68	0.20	n/a
	167	2.01	2.37	1.84	2.29	1.14	1.70	0.87	0.67	0.08	n/a

data. It also appears that since applied water is generally lower in IDC (see Table 2), it is likely that the infiltration of precipitation in IDC is estimated higher compared with those in DPLA. By increasing the curve numbers in IDC, the infiltration of precipitation can be decreased which will lead to increased applied water with increased ETaw and decreased ETp. Overall, however, the values from IDC and DPLA are reasonably close given the fact that there was no effort to calibrate IDC to match values from DPLA.

Similarly, Table 3 shows the comparison of IDC and DPLA values for rice. As for Table 2, IDC results were obtained by setting the K_{sat} values for grid cells that include rice fields to 0.01 micrometers/sec. It can be seen that ET values are generally lower in IDC than DPLA, with the exception of 1998. For 1998, ET values are closer to each other. It appears that due to different ET rates, applied water and ETaw are also lower in IDC for years 1999 through 2001. Since ET rates are similar for 1998, these values are also close to each other for 1998. Overall, the results match relatively well compared to the results for non-ponded crops.

Table 3. Comparison of IDC results for rice to the values obtained from DPLA with K_{sat} values at cells with rice set to 0.01 micrometers/sec (all values are in ac-ft/ac; n/a = not applicable)

		ET		AW		ETaw		ETp		D	
Water Year	DAU	IDC	DPLA	IDC	DPLA	IDC	DPLA	IDC	DPLA	IDC	DPLA
1998	142	3.32	2.50	5.27	4.36	2.93	2.48	0.37	0.02	0.55	n/a
	144	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n/a
	163	2.78	2.50	4.49	4.22	2.47	2.40	0.29	0.10	0.51	n/a
	164	2.94	2.55	4.75	4.29	2.61	2.44	0.30	0.12	0.50	n/a
	166	3.49	2.53	5.87	4.25	3.16	2.42	0.30	0.12	0.66	n/a
	167	3.49	2.50	5.85	4.21	3.16	2.40	0.30	0.10	0.65	n/a
1999	142	3.32	3.30	5.40	7.73	3.02	3.19	0.27	0.12	0.53	n/a
	144	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n/a
	163	2.78	3.30	4.59	6.18	2.54	3.10	0.22	0.20	0.47	n/a
	164	2.94	3.26	4.85	5.98	2.68	3.06	0.23	0.20	0.49	n/a
	166	3.49	3.30	5.97	7.76	3.23	3.09	0.23	0.21	0.65	n/a
	167	3.49	3.30	5.94	6.18	3.22	3.10	0.23	0.20	0.65	n/a
2000	142	3.32	3.23	5.38	5.34	2.99	3.05	0.30	0.19	0.53	n/a
	144	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n/a
	163	2.78	3.39	4.58	5.78	2.53	3.29	0.23	0.10	0.47	n/a
	164	2.94	3.31	4.85	5.62	2.67	3.19	0.24	0.13	0.49	n/a
	166	3.49	3.37	5.96	5.73	3.21	3.26	0.25	0.11	0.65	n/a
	167	3.48	3.40	5.95	5.79	3.21	3.30	0.24	0.10	0.65	n/a
2001	142	3.32	3.45	5.43	5.71	3.03	3.25	0.26	0.20	0.53	n/a
	144	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n/a
	163	2.78	3.60	4.62	5.96	2.56	3.40	0.20	0.20	0.47	n/a
	164	2.94	3.54	4.89	5.90	2.70	3.34	0.21	0.20	0.49	n/a
	166	3.49	3.59	5.97	5.96	3.22	3.39	0.24	0.20	0.65	n/a
	167	3.49	3.60	5.99	5.96	3.24	3.40	0.21	0.20	0.65	n/a

7 Running IDC

IDC can be executed as a stand-alone model or it can be linked to other simulation models that operate on finite-element or finite-difference type computational grids. Both the source code and the compiled executables are available for download from the IWFM web site at http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/index.cfm. IDC, either executed as a stand-alone model or linked to other simulation models, requires a main control input file that lists the names of data files used for the simulation, the simulation period and length of time step, as well as the output options. Depending on the specifications listed in the input data files, one or more output files are generated. These files store simulated water budget information at each subregion and they are in native Fortran binary format. Another program, Budget.exe, is required to process these files and generate water budget tables in ASCII text format. Budget.exe is also available for download from IWFM web site. Next, the IDC's time-tracking feature as well as input files that are used and output files that are generated by IDC are discussed.

7.1 Simulation Time Tracking

To better represent the temporal distribution of input and output data, IDC keeps track of the actual date and time of each time step in a simulation period. Each data entry in input time series data files is required to have a date and time stamp which allows IDC to retrieve time series data correctly. This, in return, allows the user to maintain a single set of time series input data files for applications where the starting and ending date and time of the simulation may change. For example, during the calibration stage of a project, the simulation is run for two periods: calibration period and the verification period. In a time tracking simulation, time series input data files can be prepared so that the data covers both the calibration and verification periods. Then the same time series data files can be used for both calibration and verification runs without the need for modification. Since a time tracking simulation keeps track of actual date and time of each of the simulation time steps, IDC can retrieve the correct data from the time series data files.

Time tracking simulations allow usage of HEC-DSS files as well as ASCII text files for time series data input and output. HEC-DSS is a database format designed by Hydrologic Engineering Center (HEC) of U.S. Army Corps of Engineers specifically for time-series data encountered in hydrologic applications. These files allow efficient storage and retrieval of hydrologic time series data, and HEC offers free utilities (HEC-DSSVue and DSS Excel add-in) for manipulation, visualization and analysis of data stored in DSS files. These utilities and instructions on how to use DSS files can be downloaded from HEC web site at www.hec.usace.army.mil.

Another advantage of time tracking simulations is that results that are printed to output files have date and time stamps associated with them. This allows easy comparison of simulation results to observed values which generally come with the date and time of observation.

7.1.1 Length of Simulation Time Step

In order to be consistent with the standards of HEC-DSS database files, IDC restricts the length of simulation time step that can be used in an application. The allowable time step lengths are listed in Table 4.

Table 4. List of allowable time step lengths in IDC simulations

Time Step Length	IDC Notation
1 minute	1MIN
2 minutes	2MIN
3 minutes	3MIN
4 minutes	4MIN
5 minutes	5MIN
10 minutes	10MIN
15 minutes	15MIN
20 minutes	20MIN
30 minutes	30MIN
1 hour	1HOUR
2 hours	2HOUR
3 hours	3HOUR
4 hours	4HOUR
6 hours	6HOUR
8 hours	8HOUR
12 hours	12HOUR
1 day	1DAY
1 week	1WEEK
1 month	1MON
1 year	1YEAR

7.1.2 Time Step Format

In IDC, start and end date and time of simulation period as well as the date and time of each data entry in time series data input files are required to be specified by using a time stamp. The format of the time stamp is as follows:

MM/DD/YYYY_hh:mm

where

MM	=	two digit month index;
DD	=	two digit day index;
YYYY	=	four digit year;
hh	=	two digit hour in terms of military time (e.g. 1:00pm is represented as 13:00);
mm	=	two digit minute.

The time is represented in military time and midnight is referred to as 24:00. For instance, 05/28/1973_24:00 represents the midnight on the night of May 28, 1973. Another example is the starting date and time of a simulation period: if the initial conditions for a daily simulation is given for the end of September 30, 1975, then the time stamp for the starting date and time of the simulation will be 09/30/1975_24:00. The first simulation result will be printed for October 1, 1975 at midnight with the time stamp 10/01/1975_24:00.

7.1.3 Preparation of Time Series Data Input Files

The user is allowed to use a mixture of ASCII text and DSS files for time series input data. In preparing these files, the rules listed below should be followed:

1. The data should have a regular interval. Gaps in the data are not allowed. For instance, if the data is monthly a value for every month should be entered.
2. The time stamp of the data represents the end of the interval for which the data is valid. For instance, in monthly time series evapotranspiration data, a data point time stamped with 08/31/1995_24:00 represents the evapotranspiration that occurred in August of 1995. As another example, if the starting date and time of the simulation period is 12/31/1970_24:00 (i.e. initial conditions are given at the midnight of

December 31, 1970) in a daily simulation, then IDC will search for the time series data time-stamped as 01/01/1971_24:00 (data for January 1st in 1971) in the time series input files.

3. The smallest interval that can be used for time series data is 1 minute.
4. A time series input data can be constant throughout the simulation period. If an ASCII text file is used for data input, the time stamp for the constant value can be set to a date and time that is greater than the ending date and time of the simulation period. For instance, if the simulation period ends at 06/15/2003_18:00 (6:00pm on June 15, 2003), then the constant value can have a time stamp 12/31/2100_24:00 (midnight on the night of December 31, 2100). IDC reads the constant value for the midnight of December 31, 2100 and uses this value for all simulation times before this date and time. Generally, time series input files include conversion factors to convert only the “spatial” component of the input data unit. The temporal unit is deduced from the time interval of the input data. In the case of constant time series data, IDC is not able to obtain the time interval and, hence, the temporal unit. If a constant value for time series data is used, the user should make sure that appropriate conversion factors are supplied so that the temporal and spatial units of the input data are consistent with those used internally during the simulation. Time series data that is constant can also be represented in DSS files but this is not suggested.
5. For rate-type time series data (e.g. evapotranspiration data), the time unit is assumed to be the interval of data. For instance, if the evapotranspiration data is entered monthly, IDC assumes that the time unit of the evapotranspiration rates is 1 month. When time series data is a constant value for the entire simulation period IDC has no

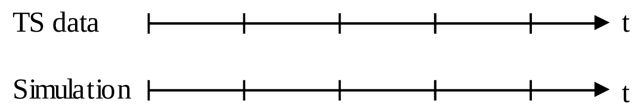
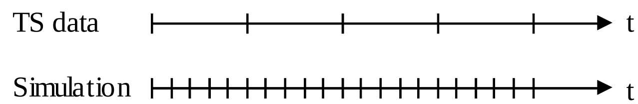
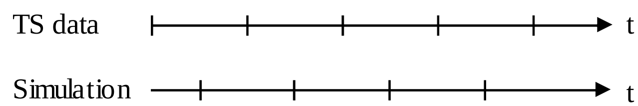
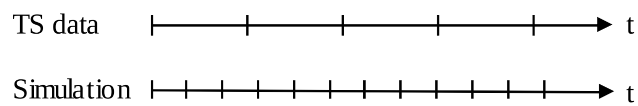
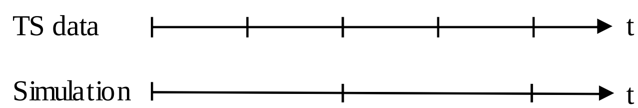
way to figure out the time unit of the input data. In this case the user should make sure that the time unit of data is the same as the consistent time unit of simulation.

6. For recycled time series data (e.g. fraction of total urban water that is used indoors given for each month but do not change from one year to the other), the year of the time stamp can be set to 4000. Year 4000 is a special flag for IDC such that it replaces year 4000 with the simulation year to retrieve the appropriate data from the input file. As an example consider the time series data in Table 5 for the fraction of total urban water that is used indoors. This data set represents that for the initial third of each simulation year the urban water indoors usage fraction is 0.7, for the second third it is 0.5 and for the last third it is 0.35. Recycled time series data can be used in both ASCII text and DSS files. If a monthly time series data is to be recycled the user should enter the time stamp for the last day of February as 02/29/4000_24:00 to address both the leap and non-leap years.
7. The interval of time series data is required to be synchronized with the simulation time step. Table 6 shows examples of accepted and unaccepted situations. It should be noted that IDC will continue to read data from the input files even if the data interval is not properly synchronized with the simulation time step. However, in such cases there is no guarantee that the correct data will be retrieved from the input file.

Table 5. Example for the representation of recycled time series data

Time Stamp	Fraction of Urban Indoors Water
04/30/4000_24:00	0.70
08/31/4000_24:00	0.50
12/31/4000_24:00	0.35

Table 6. Examples of acceptable and unacceptable cases for the synchronization of time series data interval and the simulation time step

Situation	Graphical Representation	Accepted
Monthly time series data, monthly simulation		Yes
Monthly time series data, daily simulation		Yes
Monthly time series data, monthly simulation (TS data times don't match simulation times)		No
Monthly time series data, weekly simulation		No
Monthly time series data, yearly simulation		No

Therefore, it is up to the user to ensure correct synchronization between the input data and the simulation time step.

7.2 Input and Output Data File Types

IDC can access multiple file formats: (i) ASCII text, (ii) Fortran binary, and (iii) HEC-DSS files. The user can use several file formats in a single application. For instance, some of the input time series data can be read from HEC-DSS files whereas the rest can be read from ASCII text files. Some of the time series simulation results can be printed out to ASCII text files and the others can be printed out to HEC-DSS files.

Although IDC allows usage of several file formats in a single application, some of the input and output files are required to be in specific formats. For instance, all budget output files generated by IDC and read in by Budget post-processors are required to be in Fortran binary format. Another example is the main control input file for all IDC: this file is required to be in ASCII text file format.

IDC recognizes the file formats from the 3-letter file name extensions. Table 7 lists the extensions that are recognized by IDC for each of the file formats.

Table 7. File name extensions recognized by IDC

File Type	Recognized File Name Extensions
ASCII	.DAT .TXT .OUT .IN1 .IN2 .BUD
Fortran binary	.BIN
HEC-DSS	.DSS

7.3 Input Files

Input files in IDC include comment lines as well as the input data itself. A line with one of "C", "c" or "*" at the first column is identified as a comment line. The inclusion of comment lines allows IDC files to be self-documenting; the purpose of each file along with the description of each input data are already included in IDC input file templates, and the user can include explanations for the data development directly in the input files using the comment lines.

A schematic representation of IDC input file structure is given in Figure 17. A Main Control Data File serves as the starting point for an IDC simulation. The Main Control Data File lists the names of the data files that include grid nodal x-y coordinates, element configuration data, precipitation and evaporation data, list of elements that are covered by lakes or reservoirs where root zone flow processes are not simulated, and the root zone parameters. The Main Control Data File also lists the beginning and ending date and time of the simulation as well as the simulation time step length. Factors to convert IDC simulation units into desired units of output are also listed in this file.

Root Zone Parameter File that is listed in the Main Control Data File acts as a gateway to all the parameters and data files required for the simulation of the root zone flow processes and water demand computations. This file includes names of gateway data files required for the simulation of non-ponded crops, ponded crops, urban lands, and lands with native and riparian vegetations. It also includes file names for simulation output, soil parameters at each cell and the destination for the surface runoff generated at each cell. Gateway files for non-ponded crops, ponded-crops, urban lands and lands with native and riparian vegetation act as containers for additional data file names and parameters that are

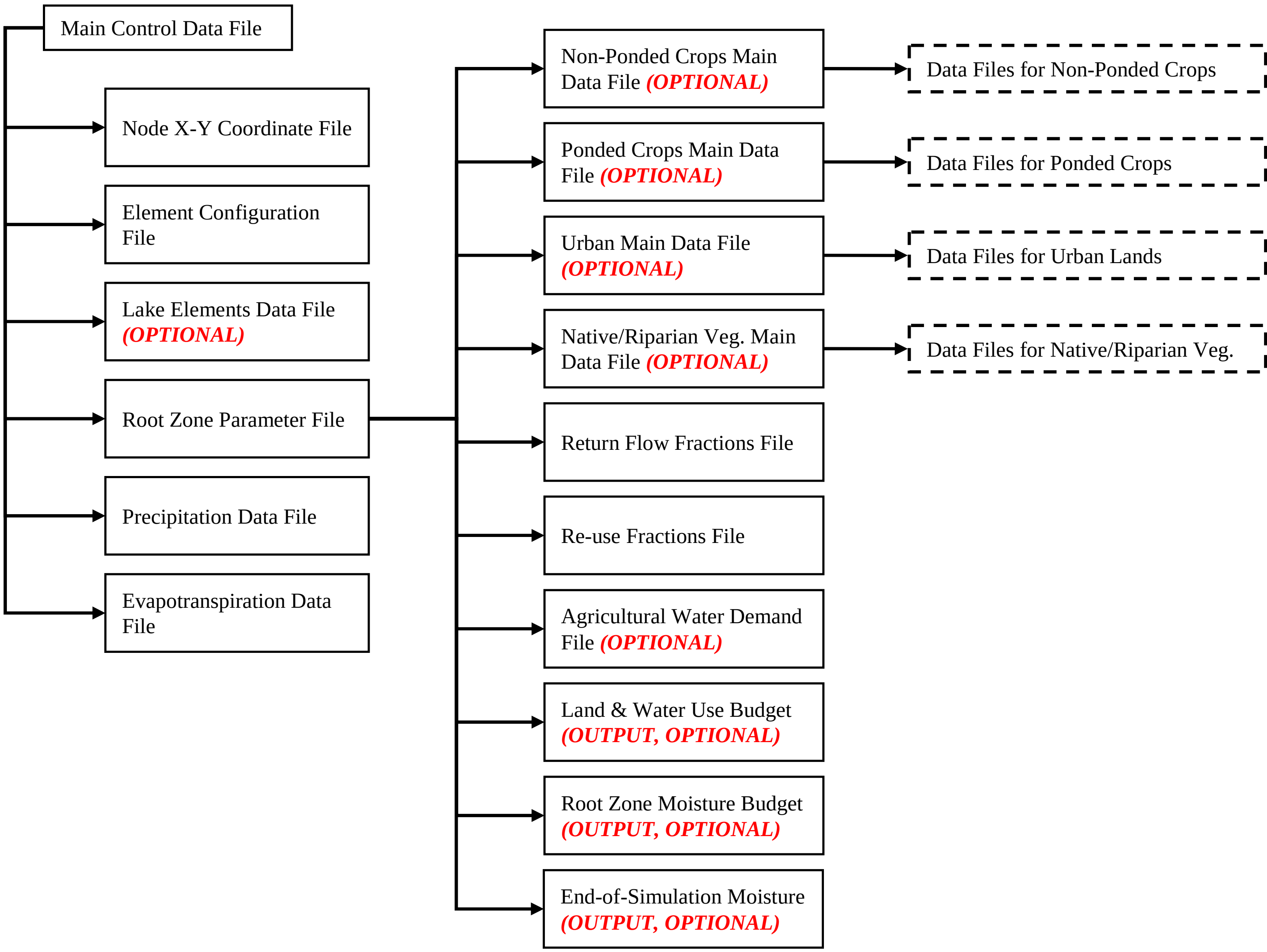


Figure 17. Schematic representation of the IDC input file structure

necessary to simulate the flow processes and water demands (if applicable) for these land-use types. These gateway files provide a structure for the user to group related data files as well as turn on or off the simulation of particular land use types in an application. For instance, by leaving blank the name of the gateway file for non-ponded crops in the Root Zone Parameter File, the user can easily omit the simulation of flow processes for non-ponded crops. This feature allows easy implementation of scenario studies where a particular land-use type is assumed to be non-existent with respect to a base-case scenario.

Each land-use type (non-ponded crops, ponded-crops, urban or native and riparian vegetation) include a data file that lists the area of each land-use type at a grid cell. These areas can be entered either as absolute areas or as fractions of the total cell area. In either case, IDC normalizes all areas (given as absolute areas or fractions) specified for a grid cell and converts all specified values into fractions of the cell area. However, whichever option is used to specify the land-use areas at a grid cell, it has to be consistent for all land-use types. For example, if the areas of non-ponded crops at a cell are specified as fractions, then areas for the ponded crops, urban lands and lands with native and riparian vegetation should also be specified as fractions. Otherwise, the total cell area will be incorrectly divided into the land-use types.

7.4 Output Files

IDC produces several optional output files. In the Root Zone Parameter File, the user can specify file names to which soil moisture as well as land and water use budgets are printed for 4 main land-use types at each subregion. These files are created in binary format for run-time efficiency and to save computer storage space. A post-processing tool, Budget, which is available for download from the IDC web site and discussed later in this document is required to process these binary files and create tables in ASCII text file format.

Optionally, IDC can generate an end-of-simulation moisture content output file that is already in ASCII text format. This file lists soil moisture for each land-use type at each element. The name for this file is specified in the Root Zone Parameter File. First, soil moisture content for non-ponded crops is printed, then those for ponded-crops and urban are printed. Finally, moisture contents for native and riparian vegetations are displayed.

The soil moisture and land and water use budget files specified in the Root Zone Parameter File stores information for 4 main land-use types at each subregion. Budget information for individual non-ponded or ponded crops are not stored in these files. Optionally, IDC can generate budget files for specific non-ponded and ponded crops at each subregion. This can be achieved by specifying crop codes and output file names in non-ponded and ponded parameter files. As mentioned earlier, the generated files will be in native binary format and the user will need Budget post-processor to process these files and generate tables in ASCII text format. The usage of Budget post-processor will be explained next.

7.5 Budget Post-Processor

IDC prints out its results into binary files to decrease the computer run times as well as the size of the output files. The information in these binary files cannot be displayed directly; instead, they need to be processed to generate understandable information in a table format. The Budget post-processor is created for this purpose and it is available for download from the IDC's web site at http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IDC/index_IDC.cfm.

Budget post-processor can process multiple binary files at the same time. The user specifies the number of binary files to be processed, the names of the binary files and the output files where the processed results will be printed out.

For each binary file to be processed the user can choose the “locations” for which the IDC results will be listed in a tabulated form. A location can either be a subregion or a set of specified land-uses at a subregion. For instance, the user can specify names for root zone moisture, and land and water use budget files in the Root Zone Parameter File (Figure 17). For these files, a location is a subregion. If the model has 20 subregions, then the user can choose in the Budget post-processor to process these two binary files and generate tabulated data for all or some of the subregions.

Similar output file names can also be specified for non-ponded and ponded crops as well as urban, native vegetation and riparian vegetation lands. In this case, a location will be a land-use and subregion combination. For instance, if the user chooses to generate binary soil moisture budget file for 4 crops (e.g. grain, alfalfa, corn and sugar beets), the first location for the processed and tabulated data will be grain in the first subregion, second location will be alfalfa in the first subregion, third location will be corn in the first subregion, etc. Fifth location will be grain in the second subregion.

By using the output features of IDC and Budget post-processor the user can obtain detailed land and water use as well as soil moisture budgets for total agriculture, urban, and native and riparian vegetation lands as well as for specific crops in each subregion.

7.6 Linking IDC to Other Models

The source code of IDC has been compiled into a dynamic link library (DLL) and the procedures necessary to link IDC to other models have been exported. The models that are using IDC need to be linked to the IDC DLL.

When IDC is linked to other models it still requires the same input data files that are utilized when IDC is used as a stand-alone model. This means that some information that is used by the linking model may need to be re-structured in a format that IDC expects. For instance, the linking model may already be using precipitation data for other processes it simulates. Since IDC also requires precipitation as input the same or additional precipitation data needs to be re-structured into the format that IDC expects. Another information that needs to be redefined in a format that IDC requires is the configuration of the computational grid. If the linking model utilizes a finite-element grid, it is likely that the format of the grid configuration data for the linking model is in a different format than IDC requires. In this case, the grid configuration needs to be redefined in the format that IDC expects to read. Similarly, if the linking model utilizes a finite-difference grid, the grid configuration should be redefined as if it is a finite-element grid in the format that IDC expects.

To successfully link IDC to other models, the modeler needs to know the interfaces to the exported procedures in the IDC DLL. Next, the exported procedures and their interfaces are given.

7.6.1 Procedure Interfaces

i. IDC_GetMainControlData

Given the name of the Main Control Data File, this procedure reads information stored in this file and initializes the simulation time period.

```
FUNCTION IDC_GetMainControlData(LenFileName,MainFileName) RESULT(iStat)
   INTEGER,INTENT(IN)                          :: LenFileName
   CHARACTER(LEN=LenFileName),INTENT(IN) :: MainFileName
   INTEGER                                     :: iStat
END FUNCTION IDC_GetMainControlData
```

LenFileName : Length of the name for the Main Control Data file.

MainFileName : Name of the Main Control Data File

ii. IDC_InitApp

Using the information included in the data files that are listed in the Main Control Data File, this procedure instantiates the simulation grid, precipitation, evapotranspiration and root zone components for the simulation.

```
FUNCTION IDC_InitApp() RESULT(iStat)
   INTEGER :: iStat
END FUNCTION IDC_InitApp
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

iii. IDC_AdvanceTime

This procedure advances the time step for IDC and generates the new time stamp using the length of time step specified in the Main Control Data File. The new time stamp is used to read locate and read data from the time-series input data files.

```
FUNCTION IDC_AdvanceTime() RESULT(iStat)
   INTEGER :: iStat
END FUNCTION IDC_AdvanceTime
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

iv. IDC_GetTimeSeriesData

This procedure reads data from time-series input files for the corresponding time step in the simulation.

```
FUNCTION IDC_GetTimeSeriesData() RESULT(iStat)
    INTEGER :: iStat
END FUNCTION IDC_GetTimeSeriesData
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

v. IDC_ComputeWaterDemand

This procedure computes applied water demand for ponded and non-ponded agricultural crops as well as for urban areas.

```
FUNCTION IDC_ComputeWaterDemand() RESULT(iStat)
    INTEGER :: iStat
END FUNCTION IDC_ComputeWaterDemand
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

vi. IDC_ZeroSupply

This procedure resets the water supply to each element.

```
FUNCTION IDC_ZeroSupply() RESULT(iStat)
    INTEGER :: iStat
END FUNCTION IDC_ZeroSupply
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

vii. IDC_SetSupplyToElem

This procedure sets the water supply to each element or to each subregion. The source of water supply can be either stream diversions or groundwater pumping. Water supply can be assigned to each element or to each subregion. If the supply is assigned to each subregion than IDC distributes the subregional water supply to individual elements in proportion to the water demand at each element in the subregion. This procedure can be called multiple times to represent a mixture of pumping and diversions to elements or subregions. When the procedure is called multiple times, IDC accumulates supplies to elements.

```
FUNCTION IDC_SetSupplyToElem(NSupply,Supply,SupplyType,Dest,DestType) RESULT(iStat)
   INTEGER,INTENT(IN) :: NSupply,SupplyType
   INTEGER,INTENT(IN) :: Dest(NSupply),DestType(NSupply)
   REAL(8),INTENT(IN)    :: Supply(NSupply)
   INTEGER                       :: iStat
END FUNCTION IDC_SetSupplyToElem
```

NSupply : Number of water supplies specified.

Supply : Water supply amounts to each element or subregion.

SupplyType : Enter 1 if source of water supply is diversions; enter 2 if the source is groundwater pumping.

Dest : Water supply destination identification number. If the supply is assigned to elements then Dest should list the element identification numbers, if supply is assigned to subregions then Dest should include subregion identification numbers.

DestType : Water supply destination type. If the water supply is assigned to elements, then enter 2; if it is assigned to subregions then enter 4.

viii. IDC_Simulate

This procedure computes the root zone and land surface flow processes.

```
FUNCTION IDC_Simulate() RESULT(iStat)
   INTEGER :: iStat
END FUNCTION IDC_Simulate
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

ix. IDC_PrintResults

This procedure prints out the results to the ouput files specified by the user. To speed up the computer run-times, IDC stores the values to be printed in cache whose size is defined by the user in thye Main Control Data File. When cache is full, the values are flushed to the output files. To trigger the flushing of the values to the output files at the end of the simulation even when the cache is not full, this procedure requires the user to specify if it is the end of simulation or not.

```
FUNCTION IDC_PrintResults(iEndOfSimulation) RESULT(iStat)
   INTEGER,INTENT(IN) :: iEndOfSimulation
   INTEGER            :: iStat
END FUNCTION IDC_PrintResults
```

iEndOfSimulation : If it is the last time step of the simulation, enter 1. Otherwise enter 0.

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

x. IDC_AdvanceState

This procedure advances the state of the root zone in time. The flow rates that are computed at the end of the time step are labeled as flow rates at the beginning of the next time step.

```
FUNCTION IDC_AdvanceState() RESULT(iStat)
   INTEGER :: iStat
END FUNCTION IDC_AdvanceState
```

iStat : Error code that is returned by the procedure; 0 represents successful execuation of the procedure.

xi. IDC_GetDeepPercAll

This procedure is used to get the deep percolation computed at all elements of the computational grid computed by IDC. These values can be used by the calling simulation model as the recharge to the groundwater.

```
SUBROUTINE IDC_GetDeepPercAll(NElements,DeepPerc)
   INTEGER,INTENT(IN)  :: NElements
   REAL(8),INTENT(OUT) :: DeepPerc(NElements)
END SUBROUTINE IDC_GetDeepPercAll
```

NElements : Number of cells in the computational grid.

DeepPerc : Deep percolation at every cell computed by IDC.

xii. IDC_GetDeepPercElement

This procedure is used to get deep percolation at a specific cell of the computational grid computed by IDC.

```
FUNCTION IDC_GetDeepPercElement(iElem) RESULT(DeepPerc)
   INTEGER,INTENT(IN) :: iElem
   REAL(8)            :: DeepPerc
END FUNCTION IDC_GetDeepPercElement
```

iElem : Identification number of the grid cell for which the deep percolation computed by IDC is required.

DeepPerc : Deep percolation at grid cell iElem computed by IDC.

xiii. IDC_GetFlowsToStreams

This procedure obtains the surface flows computed by IDC into the modeled stream nodes.

```
SUBROUTINE IDC_GetFlowsToStreams(NStrmNodes,DirectRunoff,ReturnFlow)
   INTEGER,INTENT(IN)  :: NStrmNodes
   REAL(8),INTENT(OUT) :: DirectRunoff(NStrmNodes),ReturnFlow(NStrmNodes)
END SUBROUTINE IDC_GetFlowsToStreams
```

NStrmNodes : Number of stream nodes modeled by the model that is linked to IDC. The destination of surface flows from each grid cell is specified in IDC input data files.

DirectRunoff : Direct runoff from precipitation into each of the modeled stream nodes.

ReturnFlow : Irrigation return flow into each of the modeled stream nodes.

xiv. IDC_GetElementWaterDemand

This subroutine obtains the total water demand at each grid cell computed by IDC. These demands can be used by the linking model to adjust the diversions and groundwater pumping.

```
SUBROUTINE IDC_GetElementWaterDemand(NElements,ElemDemand)
   INTEGER,INTENT(IN)  :: NElements
   REAL(8),INTENT(OUT) :: ElemDemand(NElements)
END SUBROUTINE IDC_GetElementWaterDemand
```

NElements : Number of cells in the computational grid.

ElemDemand : Total water demand at each grid cell computed by IDC.

7.6.2 Example Code That Links to IDC

For IDC to execute properly when linked to other models, it is necessary to invoke the procedures in the IDC DLL in a specific order. Figure 18 is an example code that demonstrates how another model can be linked to IDC. The code is incomplete because particular procedures to execute the linking model are not shown. The example assumes that the computational grid has 1000 cells with 100 stream nodes modeled. The linked IDC and model combination runs for 3000 time steps.

The example given in Figure 18 assumes that the aquifer and stream systems simulated by the linked model have enough storage to meet the water demand computed by

```fortran
PROGRAM Test_IDC_DLL
 IMPLICIT NONE

 !Local variables
 CHARACTER(LEN=11)    :: cFile = 'IDC_Main.in'
 INTEGER,PARAMETER :: nTimeSteps= 3000  , &
                      nElems    = 1000  , &
                      nStrms    = 100
 INTEGER              :: iStat,indx,Dest(nElems),DestType(nElems),iEndOfSimulation
 INTEGER,EXTERNAL     :: IDC_GetMainControlData,IDC_InitApp,IDC_AdvanceTime,  &
                         IDC_GetTimeSeriesData,IDC_ComputeWaterDemand,        &
                         IDC_ZeroSupply,IDC_SupplyToElem,IDC_Simulate,        &
                         IDC_PrintResults,IDC_AdvanceState
 REAL(8)              :: Supply_Diversion(nElems),Supply_GW(nElems),          &
                         DeepPerc(nElems),Demand(nElems),DirectRunoff(nStrms),&
                         RetFlow(nStrms)

 !Initialize the model
 iStat              = IDC_GetMainControlData(11,cFile)    !Read the Main Control Data
 iStat              = IDC_InitApp()                       !Instantaite model
 DestType           = 2                                   !Destination for water supply is elements
 Dest               = (/(indx,indx=1,nElems)/)            !List of all elements as destination for supply
 iEndOfSimulation = 0                                     !It is NOT end-of-simulation yet

 !Run the model
 DO indx=1,nTimeSteps
   iStat = IDC_AdvanceTime()                          !Advance time step to read proper data from input files
   iStat = IDC_GetTimeSeriesData()                    !Read the time-series data at the simulation time step
   iStat = IDC_ComputeWaterDemand()                   !Compute water demand at each element
   iStat = IDC_ZeroSupply()                           !Zero out all water supply to all elements
   CALL IDC_GetElementWaterDemand(nElems,Demand)  !Obtain the water demand at each element

   !Here, linked model computes groundwater pumping and diversions
   !  to meet water demand
   Supply_Diversion = ...
   Supply_GW        = ...

   iStat = IDC_SetSupplyToElem(nElems,Supply_Diversion,1,Dest,DestType) !Water supply as diversions
   iStat = IDC_SetSupplyToElem(nElems,Supply_GW,2,Dest,DestType)        !Water supply as pumping
   iStat = IDC_Simulate()                                      !Compute root zone/land surface flows
   IF (indx .EQ. nTimeSteps) iEndOfSimulation = 1              !Is it the last time step?
   iStat = IDC_PrintResults(iEndOfSimulation)                  !Print results from IDC
   CALL IDC_GetDeepPercAll(nElems,DeepPerc)                    !Obtain computed deep perc at all elements
   CALL IDC_GetFlowsToStreams(NStrms,DirectRunoff,RetFlow)     !Obtain the surface runoff into streams

   !Here, the linked model simulates stream and groundwater
   !  dynamics with IDC-computed deep percolation and flows
   !  into stream
     CALL LinkedModel_Simulate(DeepPerc,DirectRunoff,RetFlow,...)

   iStat = IDC_AdvanceState()                                 !Advance the state of the root zone in time
 END DO

END
```

Figure 18. Example code demonstrating the linkage of IDC to another model

IDC at all times. In certain cases, the aquifer and stream storage may be limited and the demand may not be met. In this case, iterations between the linked model and IDC may be necessary. This is a complex situation and is not considered in Figure 18.

8 References

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements: Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper 56, 300 p.

Ayers, R. S., and D. W. Westcot. 1985. Water quality for agriculture: Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper 29.

Burt, C. M., A. J. Clemmens, T. S. Strelkoff, K. H. Solomon, R. D. Bliesner, L. A. Hardy, T. A. Howell, and D. E. Eisenhauer. 1997. Irrigation performance measures: Efficiency and uniformity. Journal of Irrigation and Drainage Engineering 123, (6) (Nov-Dec): 423-442

CADWR 2005. California Water Plan Update 2005, A Framework for Action. Regional Reports, Volume 3. Bulletin 160-05. California Department of Water Resources. Sacramento, CA.

CADWR 2009. IWFM: Integrated Water Flow Model. http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/index.cfm (accessed September 29, 2009)

Camp, C. R., G. D. Christenbury, and C. W. Doty. 1988. Scheduling irrigation for corn and soybeans in the southern coastal plains. *Trans. ASAE* 31, 513-518.

Campbell, G. S. 1974. A simple method for determining unsaturated hydraulic conductivity from moisture retention data. *Soil Sci.*, 117(6), 311-314.

Corwin, D. L., J. D. Rhoades, and J. Simunek. 2007. Leaching requirement for soil salinity control: Steady-state versus transient models. *Agricultural Water Management* 90(3), 165-180.

DHI (Danish Hydraulic Institute). 1999. MIKE SHE Pre- and Post-Processing User Manual. DHI Software, Hørsholm, Denmark.

Dogrul, E. C. 2007. Integrated Water Flow Model (IWFM v3.0): Theoretical documentation. Sacramento (CA): Integrated Hydrological Models Development Unit, Modeling Support Branch, Bay-Delta Office, California Department of Water Resources, variously paged.

Dudley, L. M., A. Ben-Gal, and U. Shani. 2008. Influence of plant, soil, and water on the leaching fraction. *Vadose Zone Journal* 7(2), 420-425.

Fereres, E. and M. A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. *J. Experimental Botany* 58(2), 147-159.

George, B. A., S. A. Shende, and N. S. Raghuwanshi. 2000. Development and testing of an irrigation scheduling model. *Agricultural Water Management* 46 (2), 121-136.

Gerald, C., and P. O. Wheatley. 1994. *Applied numerical analysis. Fifth edition.* Addison-Wesley Publishing Co.748 p.

Goodall, J. L., B. F. Robinson, F. M. Shatnawi, and A. M. Castronova. 2007. *Linking hydrologic models and data: The OpenMI approach*. 2007 American Geophysical Union Fall Meeting, San Francisco, CA (USA), 10-14 Dec 2007.

Gregersen, J.P., P.J.A. Gijsbers, and S.J.P. Westen. 2007. OpenMI: Open modelling Interface. Journal of Hydroinformatics, 9(3), 175-191.

Heng, L. K., T. Hsiao, S. Evett, T. Howell, and P. Steduto. 2009. Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agronomy Journal* 101(3), 488-498.

Kavvas, M. L., Z. Q. Chen, C. Dogrul, J. Y. Yoon, N. Ohara, L. Liang, H. Aksoy, M. L. Anderson, J. Yoshitani, K. Fukami, and T. Matsuura. 2004. Watershed Environmental Hydrology (WEHY) model based on upscaled conservation equations: Hydrologic Module. J. Hydrol. Eng. 9:450-464.

Kincaid, D. C., and D. F. Heerman. 1974. Scheduling irrigations using a programmable calculator. ARS-NC-12, USDA Agric. Res. Service, Lincoln, Nebraska.

Kirda, C. 2002. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. In *Deficit irrigation practices: Water reports 22*, Food and Agriculture Organization of the United Nations, Rome.

Leavesley, G. H., R. W. Lichty, B. M. Troutman, and L. G. Saindon. 1983. Precipitation-Runoff Modeling System: User's Manual: U.S. Geological Survey Water-Resources Investigations 83-4238.

Markstrom, S. L., R. G. Niswonger, R. S. Regan, D. E. Prudic, and P. M. Barlow. 2008. GSFLOW--Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res., 12, 513-522.

Orang, M. N., J. S. Matyac, and R. L. Synder. 2004. Consumptive Use Program (CUP) model. In *IV International symposium on irrigation of horticultural crops*, ed. R. L. Synder. Acta Hort., 664, 461-468, ISHS.

PRISM [PRISM Climate Group]. 2009. Oregon State University, http://www.prismclimate.org (accessed September 10, 2009).

Raes, D., P. Steduto, T. C. Hsiao, and E. Fereres. 2009. AquaCrop – The FAO crop model to simulate yield response to water. FAO Land and Water Division, FAO, Rome.

Rawls, W. J., D. L. Brakensiek, and K. E. Saxton. 1982. Estimation of soil water properties. T. ASAE, 25(5), 1316-1320.

Ritchie, J. T. 1981. Soil water availability. Plant and Soil, 58, 327-333.

Schmid, W., R. T. Hanson, T. Maddock III, and S. A. Leake. 2006. User guide for the farm process (FMP1) for the US Geological Survey’s modular three-dimensional finite-difference groundwater flow model, MODFLOW-2000. (Book 6). Reston (VA): US Geological Survey. 127 p. Techniques and Methods 6-A17. Available at: http://pubs.usgs.gov/tm/2006/tm6A17/

Schroeder, P. R., T. S. Dozier, P. A. Zappi, B. M. McEnroe, J. W. Sjostrom and R. L. Peton. 1994. The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3, EPA/600/R-94/168b. U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.

Smith, M. 1991. CROPWAT: A computer program for irrigation planning and management. FAO Land and Water Development Division, FAO, Rome.

Snyder, R. L., M. N. Orang, J. S. Matyac, S. Geng, and S. Sarreshteh. 2004. A simulation model for ET of applied water. In *IV International symposium on irrigation of horticultural crops*, ed. R. L. Synder. Acta Hort., 664, 623-629, ISHS.

Sophocleous, M. A., J. K. Koelliker, R. S. Govindaraju, T. Birdie, S. R. Ramireddygari, and S. P. Perkins. 1999. Integrated numerical modeling for basin-wide water management: The case of the rattlesnake creek basin in south-central Kansas. *Journal of Hydrology* 214, (1-4) (Jan): 179-196.

Tayfur, G., K. K. Tanji, B. House, F. Robinson, L. Teuber, and G. Kruse. 1995. Modeling deficit irrigation in alfalfa production. *Journal of Irrigation and Drainage Engineering* 121(6), 442-451.

Therrien, R., R. G. McLaren, E. A. Sudicky, and S. M. Panday. 2009. HydroGeoSphere – a three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport (Draft ed.). Groundwater Simulations Group, University of Waterloo, Waterloo, Canada.

USDA, Natural Resources Conservation Service. 1997. National engineering handbook. Washington (DC): US Department of Agriculture. Part 652, Irrigation guide.

USDA, Natural Resources Conservation Service. 2004. National engineering handbook. Washington (DC): US Department of Agriculture. Part 630, Hydrology, Chapters 9 and 10.

van Genuchten, M. T. 1985. A closed-form solution for predicting the conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892-898.

Williams, J. 2004. Water management. California Rice Production Workshop, 2004. University of California Cooperative Extension. http://ucce.ucdavis.edu/files/filelibrary/6318/36235.pdf (accessed August 5, 2009).

Williamson, A. K., D. P. Prudic, and L. W. Swain. 1989. Ground-water flow in the Central Valley, California. U. S. Geologic Survey Professional Paper, 1401-D.

9 Appendix A. Object Model