# M e m o r a n d u m

Date: June 26, 2007

To:
1. Tariq Kadir
2. Sushil Arora
3. Francis Chung

Emin Can Dogrul, Water Resources Engineer
Hydrology and Operations Section
Modeling Support Branch, Bay-Delta Office
From: **Department of Water Resources**

Subject: Soil Moisture Routing and Agricultural Demand Computation in IWFM Demand Calculator (IDC v1.0)

The attached technical report, “Soil Moisture Routing and Agricultural Demand Computation in IWFM Demand Calculator (IDC v1.0)”, is submitted for your perusal. This report details the underlying theory and methods for the simulation of soil moisture and runoff processes in the root zone, and the computation of agricultural water demand. Input data required to run IDC and the output data are listed. Additionally, a discussion of the differences between IDC and Consumptive Use Model (CU Model) is provided.

If additional information is required please contact me at 654-7018.

Attachment

# Soil Moisture Routing
# and
# Agricultural Demand Computation
# in
# IWFM Demand Calculator (IDC v1.0)

**Prepared by**
**Emin Can Dogrul**

**Hydrology Development Unit**
**Modeling Support Branch**
**Bay-Delta Office**
**June, 2007**

## Table of Contents


List of Figures ..... iii

1. Introduction ..... 1

2. Soil Moisture Routing in the Root Zone ..... 1

   2.1. Infiltration of Precipitation, $I_{f_p}$ ..... 3

      2.1.1. Computation of Direct Runoff, $S_r$ ..... 3

   2.2. Infiltration of Applied Water, $I_{f_{AW}}$ ..... 7

      2.2.1. Computation of Return Flow, $R_f$ ..... 8

   2.3. Evapotranspiration, $ET_{cadj}$ ..... 9

   2.4. Deep Percolation, $D_p$ ..... 13

      2.4.1. Deep Percolation Using Physically-based Computation ..... 14

      2.4.2. Deep Percolation Using Deep Percolation Fraction ..... 15

3. Computation of Irrigation Water Demands ..... 16

   3.1. Agricultural Water Demand ..... 18

      3.1.1. Seasonal Crop Application Efficiency ..... 21

      3.1.2. Re-use of Irrigation Water ..... 24

4. IDC Input and Output Data ..... 28

   4.1. Input Parameters ..... 28

      4.1.1. Parameters Related to Execution Control ..... 28

      4.1.2. Subregional Parameters ..... 28

      4.1.3. Crop Parameters ..... 28

4.1.4. Soil Parameters .....29

4.1.5. Parameters Related to Water Management .....30

4.1.6. Parameters Related to Precipitation .....30

4.1.7. Parameters Related to Simulation Output .....30

4.2. Output Data .....31

4.2.1. Standard Output Data .....31

4.2.2. Optional Root Zone Water Budget Output Data .....31

4.2.3. Optional Potential $CU_{AW}$ Output Data .....33

5. Differences between IDC and CU Model .....33

6. Appendix A .....40

6.1. Generation of Figure 4 .....40

6.2. Generation of Figure 6 .....41

6.3. Generation of Figure 8 .....41

7. References .....42

## List of Figures

**Figure 1** Ratio of actual crop evapotranspiration to crop evapotranspiration under standard conditions as a function of the ratio of root zone moisture to field capacity ..... 13

**Figure 2** Flowchart for the simulation of the soil moisture in the root zone ..... 17

**Figure 3** A schematic representation of the root zone profile ..... 19

**Figure 4** Results of the first test problem (see Appendix A for the settings used in creation of this chart) ..... 35

**Figure 5** Inflow and outflow fluxes in IDC for the first test problem ..... 36

**Figure 6** Results of the second test problem (see Appendix A for assumptions used in creation of this chart) ..... 37

**Figure 7** Inflow and outflow fluxes in IDC for the second test problem ..... 38

**Figure 8** Results for the third test problem (see Appendix A for assumptions used in creation of this chart) ..... 40

# 1. Introduction

IWFM Demand Calculator (IDC) is the stand alone soil moisture routing component of the Integrated Water Flow Model (IWFM) that is developed and maintained by the Bay-Delta Office of California Department of Water Resources (DWR, 2007). It is a flexible utility that routes precipitation and irrigation water through root zone using physically-based simulation methods. Using moisture routing techniques, it also computes land-use based water demands for user-specified crop distributions. Therefore, it is a valuable tool that can be used in water resources planning and management studies.

IDC allows the user to divide the modeled region into multiple subregions. The acreages of agricultural crops, urban and native vegetation lands in each subregion are then defined. These land use acreages drive the routing of soil moisture in the root zone as well as the computation of crop irrigation water demands. In IDC irrigation water demands throughout the simulation period are computed as a function of soil properties, crop properties and initial soil moisture content that is a result of previous precipitation and irrigation events. Therefore, computation of irrigation water demands in IDC is tightly connected to the routing of soil moisture in the root zone. This document explains the soil moisture routing scheme and the irrigation water demand computation in IDC.

# 2. Soil Moisture Routing in the Root Zone

The soil moisture in the root zone is a function of the moisture that is already available in the soil, the moisture inflow in terms of infiltration of the precipitation and

applied water, and the moisture outflow in terms of evapotranspiration and deep percolation. The conservation equation for the root zone can be written as

$$D_r \frac{\theta_r^{t+1} - \theta_r^t}{\Delta t} = I_{f_p} + I_{f_{AW}} - ET_{cadj} - D_p \qquad (1)$$

where

| | | |
|---|---|---|
| $D_r$ | = | thickness of the root zone, (L); |
| $\theta_r^{t+1}$ | = | soil moisture content in the root zone at the end of time step, (L/L); |
| $\theta_r^t$ | = | soil moisture content in the root zone at the beginning of time step, (L/L); |
| $I_{f_p}$ | = | infiltration of precipitation, (L/T); |
| $I_{f_{AW}}$ | = | infiltration of applied water, (L/T); |
| $ET_{cadj}$ | = | actual crop evapotranspiration, (L/T); |
| $D_p$ | = | deep percolation, (L/T); |
| $\Delta t$ | = | length of time step, (T). |

In IDC it is assumed that the root zone thickness, $D_r$, for a particular crop does not change during the lifetime of the crop. The goal is to solve equation (1) to compute $\theta_r^{t+1}$, the soil moisture content at the end of the time step, with known values of $D_r$, $\Delta t$ and $\theta_r^t$. In order to solve (1), one needs to compute $I_{f_p}$, $I_{f_{AW}}$, $ET_{cadj}$ and $D_p$. In the following sections the methods that IDC uses to compute each of these terms will be detailed.

## 2.1. Infiltration of Precipitation, $I_{f_p}$

Infiltration is the movement of water from the ground surface into the soil. The amount of precipitation that infiltrates into the soil is the portion of the precipitation that is left after surface runoff:

$$I_{f_p} = P - S_r \tag{2}$$

where

$I_{f_p}$ = infiltration of precipitation, (L/T);

$P$ = precipitation, (L/T);

$S_r$ = direct runoff, (L/T).

Solution of (2) requires the estimation of the direct runoff, $S_r$. In the following section, methods used in IDC to compute $S_r$ are detailed.

### 2.1.1. Computation of Direct Runoff, $S_r$

In IDC, direct runoff is computed using a rainfall-runoff relation, known as SCS method, developed by the National Resources Conservation Service (formerly known as Soil Conservation Service) for watersheds that are not gauged for runoff. The SCS method estimates the amount of precipitation that becomes direct runoff, versus the quantity that infiltrates into the root zone. This method is based on a curve number (CN) which indicates runoff potential. Higher curve numbers amount to higher runoff potentials. Each curve number has been developed for a specific land use type, soil type, management practice, and antecedent moisture condition (USDA, 1985).

Estimation of direct runoff depends on the quantity of precipitation, and the value of the retention parameter. The retention parameter, $S_{max}$, is a function of the curve number and the soil moisture, and represents the infiltration occurring once runoff begins (Schroeder, et al.,1994). The retention parameter for a specific land use type, soil type, and management practice is expressed as follows (USDA, 1985):

$$S_{max} = \frac{1000}{CN} - 10 \tag{3}$$

where

$S_{max}$ = retention parameter for dry antecedent moisture conditions, (L);

CN = curve number specified for a combination of land use type, soil type and management practice, (dimensionless).

It should be noted that usage of the curve numbers, CN, listed in the original documentation of the SCS method produce retention parameter, $S_{max}$, in units of inches (USDA, 1985). In order to use equation (3) to compute $S_{max}$ in units other than inches, one needs to modify CN values accordingly. As an example, consider the computation of $S_{max}$ in units of feet. A modified curve number, CN*, can be computed as follows:

$$S^*_{max} = \frac{S_{max}}{12} = \frac{\frac{1000}{CN} - 10}{12} = \frac{1000}{CN^*} - 10 \tag{4}$$

where

$S^*_{max}$ = retention parameter in units of feet;

CN* = modified curve number for the computation of $S^*_{max}$.

Rewriting equation (4) to express CN* in terms of CN, one obtains

$$CN^* = \frac{12000 \times CN}{110 \times CN + 1000} \tag{5}$$

Similar expressions for CN* to compute $S^*_{max}$ in other units (other than inches) can also be derived. The user should make sure that properly modified curve numbers based on the units utilized in the particular modeling project are obtained before inputting these data into IDC.

Equation (3) is valid for dry antecedent moisture conditions in which the soil moisture content of the soil is less than half of the difference between the field capacity and the wilting point. For higher values of soil moisture content, IDC adjusts the retention parameter with respect to the value of the soil moisture, as documented in the HELP Model Documentation (Schroeder, et al., 1994):

$$S = \begin{cases} S_{max}\left[1 - \dfrac{\theta_r - \left[\left(\theta_f - \theta_{wp}\right)/2\right]}{\eta_T - \left[\left(\theta_f - \theta_{wp}\right)/2\right]}\right] & \text{for } \theta_r > \left[\left(\theta_f - \theta_{wp}\right)/2\right] \\ S_{max} & \text{for } \theta_r \le \left[\left(\theta_f - \theta_{wp}\right)/2\right] \end{cases} \tag{6}$$

where

$\theta_r$ = soil moisture, (L/L);

$\theta_f$ = field capacity, (L/L);

$\eta_T$ = total porosity, (L/L);

$\theta_{wp}$ = wilting point, (assumed to be negligible in IDC) (L/L);

S = retention parameter modified with respect to the soil moisture, (L).

As stated in equation (6), the retention parameter is calculated based on the amount of soil moisture in the soil with respect to the field capacity. Assuming that the wilting point is negligible, the retention in the soil will be less when the soil moisture exceeds 50% of the field capacity in the soil (see equation (6)).

The SCS method sets a constraint, in which the precipitation must exceed 20% of the retention parameter in order for direct runoff to occur. The fraction of the retention parameter is referred to as the initial abstraction, and is based on an empirical relationship that was developed from field experiments performed on small watersheds. The initial abstraction refers to interception, infiltration, and surface storage, which occur prior to runoff during a storm. Given that the rainfall exceeds the amount of water necessary for interception and surface storage, the direct runoff is

$$S_r = \frac{1}{\Delta t}\frac{\left(P\Delta t - 0.2S\right)^2}{P\Delta t + 0.8S} \tag{7}$$

where

$S_r$ = direct runoff, (L/T);

$P$ = precipitation rate, (L/T);

$\Delta t$ = time period over which the precipitation rate has occurred, (T).

Direct runoff, $S_r$, is computed for each land use (i.e. type of ground cover) type over the modeled region.

The reader will notice differences in the units and the equation itself in (7) when compared to the original method (USDA, 1985). The SCS method is developed for individual storm events with durations on the order of minutes or hours. The

precipitation and retention values are originally given in units of length for the duration of the storm. IDC attempts to convert the unit of length to unit of rate in order to be able to utilize SCS method in a time-continuous simulation mode. For this reason, the term $\Delta t$ has been introduced in equation (7) in order to maintain the consistency between the units of the original method and the time-continuous simulation used in IDC.

For the computation of the direct runoff on urban lands, IDC uses equation (7) only for the pervious (i.e. unpaved) portion of the urban area. All precipitation that falls onto the impervious (i.e. paved) portion of the urban area becomes surface runoff.

As an alternative to using equation (2) to compute the infiltration of precipitation, IDC allows the user to define $I_{f_p}$ directly as an input. This alternative is introduced because the usage of SCS method at large time steps does not always produce correct infiltration and runoff values. For example, a project may require the running of IDC at a monthly time step. However, using SCS method with a monthly time step and monthly precipitation rates generally underestimates the surface runoff and, consequently, overestimates the infiltration. To overcome this problem, the user can develop direct runoff and infiltration values outside IDC using smaller time steps. Then these infiltration values can be accumulated to monthly time step and used as direct input to IDC.

## 2.2. Infiltration of Applied Water, $I_{f_{AW}}$

Infiltration of applied water in IDC is computed as

$$I_{f_{AW}} = AW - R_f \tag{8}$$

where

$I_{f_{AW}}$ = infiltration of applied water, (L/T);

AW = applied water, (L/T);

$R_f$ = return flow, (L/T).

To compute $I_{f_{AW}}$, given AW, it is necessary to compute the return flow, $R_f$, first. Next section describes the methods used in IDC to compute $R_f$.

### 2.2.1. Computation of Return Flow, $R_f$

For urban areas, entire amount of water that is used indoors becomes return flow. The amount of return flow from the agricultural lands and pervious portion of the urban lands (parks, backyards, etc) is computed based on the soil moisture content and other fluxes that occur in the root zone. First, it is assumed that all of the application water infiltrates into the soil. Then, the summation of the soil moisture that is already available in the root zone and the infiltration of precipitation and applied water less the evapotranspiration, deep percolation and field capacity becomes the return flow:

$$R_f = \max\left( \frac{D_r \theta_r}{\Delta t} + I_{f_p} + AW - ET_{cadj} - D_p - \frac{D_r \theta_f}{\Delta t} \quad , \ 0 \right) \tag{9}$$

where

$R_f$ = return flow of applied water, (L/T);

$D_r$ = rooting depth, (L);

$\theta_r$ = soil moisture content of the root zone, (L/L);

$\theta_f$ = field capacity of the root zone, (L/L);

$\Delta t$ = time period over which the return flow is computed, (T);

$I_{f_p}$ = infiltration of precipitation, (L/T);

AW = applied water, (L/T);

$ET_{cadj}$ = crop evapotranspiration, (L/T);

$D_p$ = deep percolation, (L/T).

To solve (9) it is necessary to compute $ET_{cadj}$ and $D_p$. The methods that are used to compute these terms are explained next.

## 2.3. Evapotranspiration, $ET_{cadj}$

Evapotranspiration (ET) is the combination of two separate processes, namely evaporation and transpiration. Evaporation is the process where liquid water is converted to water vapor and removed from the evaporating surface. Transpiration consists of the vaporization of the liquid water contained in plant tissues and the vapor removal to the atmosphere. Both evaporation and transpiration depend on the available energy in terms of solar radiation and ambient air temperature, vapor pressure gradient between the air and the evaporation and transpiration surfaces, and the wind speed. When the evaporating surface is the soil surface, the degree of the shading of the crop canopy and the amount of water available at the soil surface are other factors that affect the evaporation. Transpiration depends on soil water content as well as the ability of the crop to withdraw water from the soil (Allen, et al., 1998). Since evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes, the combined process of evapotranspiration is considered in most applications.

In general, evapotranspiration is a function of weather parameters (solar radiation, air temperature, humidity and wind speed), crop factors (resistance to transpiration, crop height, crop roughness and crop rooting characteristics) and management/environmental conditions (soil salinity, land fertility, presence of hard or impenetrable soil horizons, cultivation practices, irrigation method, soil water content, etc.).

Allen, et al. (1998) describes the three evapotranspiration base concepts as follows:

(i) *Reference crop evapotranspiration ($ET_o$)*: The evapotranspiration rate from a reference surface that has adequate amount of water. The reference surface is a hypothetical grass reference crop with specific characteristics. The only factors affecting $ET_o$ are climatic parameters.

(ii) *Crop evapotranspiration under standard conditions ($ET_c$)*: The evapotranspiration rate from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. $ET_c$ reflects the effect of climatic conditions and the crop characteristics in optimum conditions. It can be related to $ET_o$ through crop coefficients as

$$ET_c = K_c ET_o \tag{10}$$

where

$ET_o$ = reference crop evapotranspiration, (L/T);

$ET_c$ = crop evaporation under standard conditions, (L/T);

$K_c$ = crop coefficient, (dimensionless).

(iii) *Crop evapotranspiration under non-standard conditions ($ET_{cadj}$)*: The evapotranspiration rate from crops grown under management and environmental conditions that differ from the standard conditions. It is also referred to as actual crop evapotranspiration in this document. It can be related to $ET_o$ as

$$ET_{cadj} = K_s K_c ET_o \tag{11}$$

where

$ET_{cadj}$ = crop evapotranspiration under non-standard conditions, (L/T);

$K_s$ = water stress coefficient, (dimensionless);

$K_c$ = adjusted crop coefficient to reflect all other stresses and environmental constraints on crop evapotranspiration, (dimensionless).

Detailed discussion of computing $ET_o$ and determining $K_c$ is provided in Allen, et al. (1998). IDC assumes that these values are computed and/or measured, and $ET_c$ for each crop type included in the model is available as a time series input parameter.

The water stress coefficient, $K_s$, is a factor that incorporates the effect of soil moisture shortage on the crop evapotranspiration rate. It can be expressed as (Allen, et al., 1998)

$$K_s = \begin{cases} \dfrac{\theta_r}{p\theta_f} & \text{if } \theta_{wp} \le \theta_r \le p\theta_f \\ 1 & \text{if } \theta_r > p\theta_f \end{cases} \tag{12}$$

where

$\theta_r$ = soil moisture content in the root zone, (L/L);

$\theta_f$ = field capacity of the root zone, (L/L);

$\theta_{wp}$ = wilting point (assumed negligible in IDC), (L/L);

p = average fraction of field capacity that can be depleted from the root zone before water stress occurs, (dimensionless).

The factor p differs from one crop to another. It normally varies from 0.3 for shallow rooted plants to 0.7 for deep rooted plants. A value of 0.5 for p is commonly used for many crops (Allen, et al., 1998). The curves provided by Schultz (1974) also suggest that a value of 0.5 for p is a reasonable estimate. Therefore, using equation (12), taking p as 0.5 and assuming wilting point is negligible, the actual crop evapotranspiration, $ET_{cadj}$, can be expressed as

$$ET_{cadj} = K_s ET_c = \begin{cases} 2\dfrac{\theta_r}{\theta_f} ET_c & \text{if} \quad 0 \le \dfrac{\theta_r}{\theta_f} \le 0.5 \\ ET_c & \text{if} \quad \dfrac{\theta_r}{\theta_f} > 0.5 \end{cases} \tag{13}$$

Figure 1 shows the ratio of $ET_{cadj}$ to $ET_c$ as a function of the ratio of the root zone soil moisture to the field capacity. This figure is a linearized version of the curve reported by Schultz (1974).

When the soil is bare, i.e. no crop coverage, then the following expression is used to compute evaporation:

$$ET_{cadj} = \begin{cases} \dfrac{\theta_r}{\theta_f} ET_c & \text{if} \quad 0 \le \dfrac{\theta_r}{\theta_f} \le 0.5 \\ \\ ET_c & \text{if} \quad \dfrac{\theta_r}{\theta_f} > 0.5 \end{cases} \tag{14}$$

where $ET_c$ denotes the bare soil evaporation when there is adequate amount of water.

## 2.4. Deep Percolation, $D_p$

Deep percolation, $D_p$, is another unknown in equation (1). IDC allows the user to choose one of two methods to compute the deep percolation. The first method is a physically-based approach that uses the soil properties, whereas the second method uses a

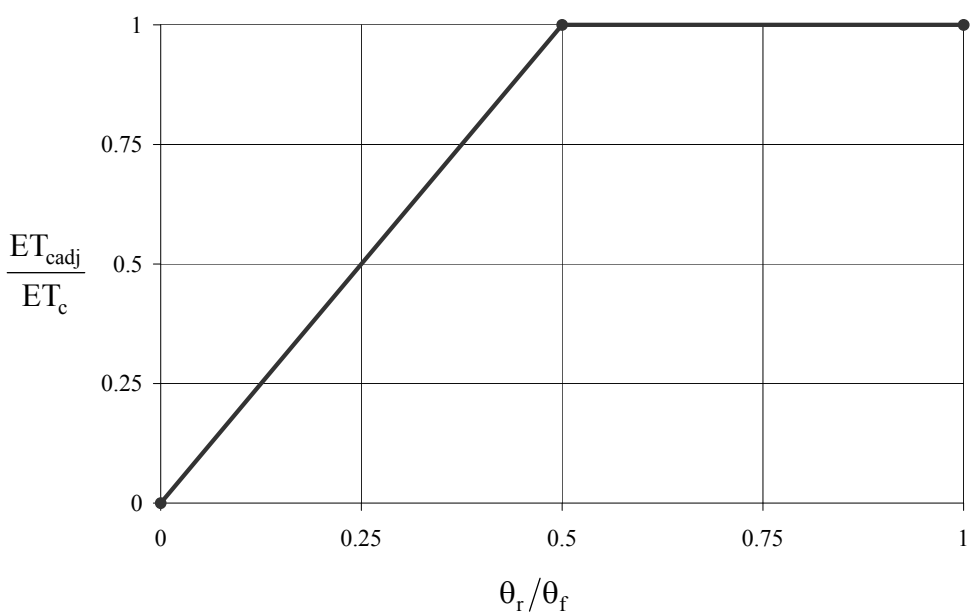


**Figure 1** Ratio of actual crop evapotranspiration to crop evapotranspiration under standard conditions as a function of the ratio of root zone moisture to field capacity

user-specified *deep percolation fraction* to distribute the soil moisture above field capacity between deep percolation and return flow.

### 2.4.1. Deep Percolation Using Physically-based Computation

Assuming that the percolation occurs at a constant pressure (i.e. $dh/dz = 1$), the rate of flow through the root zone equals the unsaturated hydraulic conductivity of the root zone (Schroeder, et al., 1994). Deep percolation does not occur when the root zone moisture is less than the field capacity. Therefore, the deep percolation from the root zone into the unsaturated zone can be written as

$$D_p = \begin{cases} 0 & \text{if} \quad \theta_r \le \theta_f \\ K_u & \text{if} \quad \theta_r > \theta_f \end{cases} \tag{15}$$

where

$K_u$ = unsaturated hydraulic conductivity of the root zone, (L/T).

The unsaturated hydraulic conductivity is computed as a non-linear function of the saturated hydraulic conductivity (Campbell, 1974):

$$K_u = K_s \left( \frac{\theta_r - \theta_{res}}{\eta_T - \theta_{res}} \right)^{3+\frac{2}{\lambda}} \tag{16}$$

where

$K_s$ = saturated hydraulic conductivity in the root zone, (L/T);

$\theta_{res}$ = residual water content, (L/L);

$\eta_T$ = total porosity of the root zone, (L/L);

$\lambda$ = pore size distribution index, (dimensionless).

In IDC, the pore size distribution index, $\lambda$, is taken to be 2. The residual water content ($\theta_{res}$) is the amount of water remaining in the soil under infinite capillary suction.

The following regression equation that was developed using mean soil texture values (Rawls et al., 1982) is used to calculate residual water content:

$$\theta_{res} = \begin{cases} 0.014 + 0.25\theta_{wp} & \text{for } \theta_{wp} \geq 0.04 \\ 0.6\theta_{wp} & \text{for } \theta_{wp} < 0.04 \end{cases} \tag{17}$$

Substituting equation (17) into (16), assuming that $\lambda$ is 2 for all soils in the model area and the wilting point, $\theta_{wp}$, is negligible, the unsaturated hydraulic conductivity can be restated as

$$K_u = K_s \left( \frac{\theta_r}{\eta_T} \right)^4 \tag{18}$$

Finally, substituting (18) into (15), the deep percolation can be written as

$$D_p = \begin{cases} 0 & \text{if } \theta_r \leq \theta_f \\ K_s \left( \frac{\theta_r}{\eta_T} \right)^4 & \text{if } \theta_r > \theta_f \end{cases} \tag{19}$$

### 2.4.2. Deep Percolation Using Deep Percolation Fraction

This approach is useful when the physically-based approach discussed above cannot be used due to the size of the simulation time step being inconsistent with the characteristic time scale of the deep percolation flow process or when values of soil parameters used in physically-based approach are not available. In this case, deep percolation is computed as a fraction of the soil moisture that is above field capacity:

$$D_p = \begin{cases} 0 & \text{if} \quad \theta_r \le \theta_f \\ f_{Dp} \dfrac{D_r\left(\theta_r - \theta_f\right)}{\Delta t} & \text{if} \quad \theta_r > \theta_f \end{cases} \tag{20}$$

where

$f_{Dp}$ = deep percolation fraction between 0 and 1; 0 means entire soil moisture above field capacity becomes return flow and 1 means entire soil moisture above field capacity becomes deep percolation.

Solution of equation (1) coupled with (19) or (20) gives the root zone moisture, $\theta_r$, and subsequently deep percolation, $D_p$. Computation of $D_p$ also allows the computation of return flow using equation (9) and infiltration of applied water using (8).

The flowchart for the routing of the soil moisture in the root zone is shown in Figure 2.

## 3. Computation of Irrigation Water Demands

An important objective of IDC is to predict the irrigation water demand based on the crop acreages, crop and soil properties, irrigation management practices and precipitation patterns. This chapter explains the methods used in IDC to compute crop irrigation water demands. It should be noted that urban indoors and outdoors water demands are required input data and IDC does not attempt to compute these demands. Therefore, the following sections include only the explanation of agricultural water demand computations.

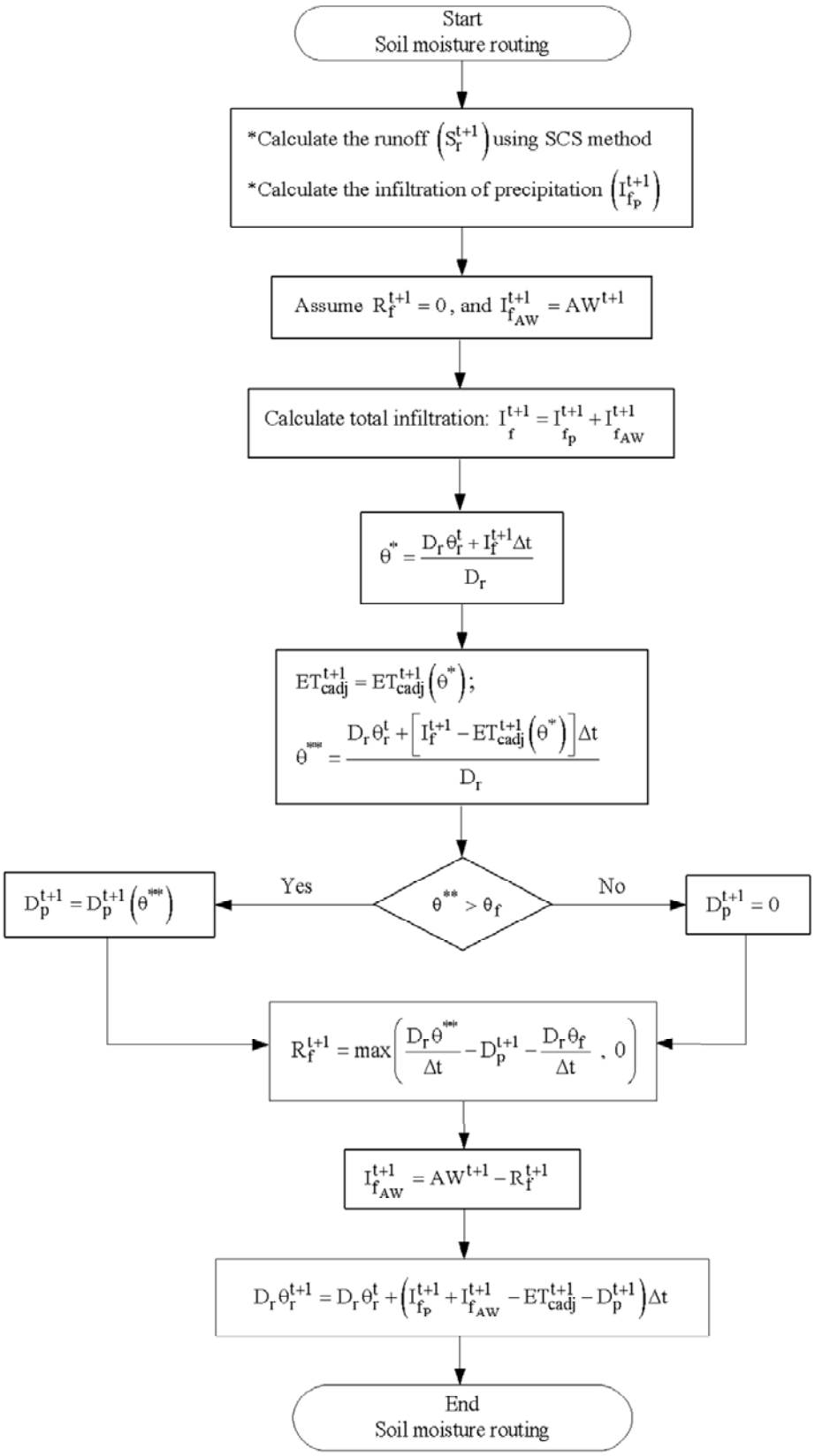


**Figure 2** Flowchart for the simulation of the soil moisture in the root zone

## 3.1. Agricultural Water Demand

The agricultural water demand is computed for each crop based on the crop consumptive use of applied water ($CU_{AW}$), seasonal application efficiency for each crop (Eff) and the amount of re-used irrigation water.

$CU_{AW}$ is the applied water needed for optimum agricultural conditions where (i) adequate crop production is guaranteed by maintaining the standard conditions so that the crops will not experience water stress, (ii) soil moisture losses as deep percolation are minimized and (iii) the minimum soil moisture requirements are met at all times. These three goals can be achieved at the same time by ensuring that the soil moisture at the root zone stays between the field capacity and the minimum soil moisture requirement (since the minimum soil moisture requirements are defined for proper crop growth, it is expected that they lie between field capacity and half of the field capacity, based on the ET computations given in previous section). A schematic representation of root zone profile and the soil moisture interval at which the three goals listed above can be achieved simultaneously are depicted in Figure 3. Therefore, when computing $CU_{AW}$, i.e. the amount of water that needs to be applied to achieve optimum agricultural conditions, a soil moisture content in this interval should be taken as a target. A reasonable and economical choice would be to target the lower end of this interval which is the minimum soil moisture requirement. Writing the mass balance equation in the root zone given in equation (1), with target soil moisture content at minimum soil moisture requirement, $\theta_{min}$, one obtains the following equation:

$$D_r \theta_{min}^{t+1} = D_r \theta_r^t + \left( I_{f_p}^{t+1} + CU_{AW}^{t+1} - ET_c^{t+1} \right) \Delta t \qquad (21)$$

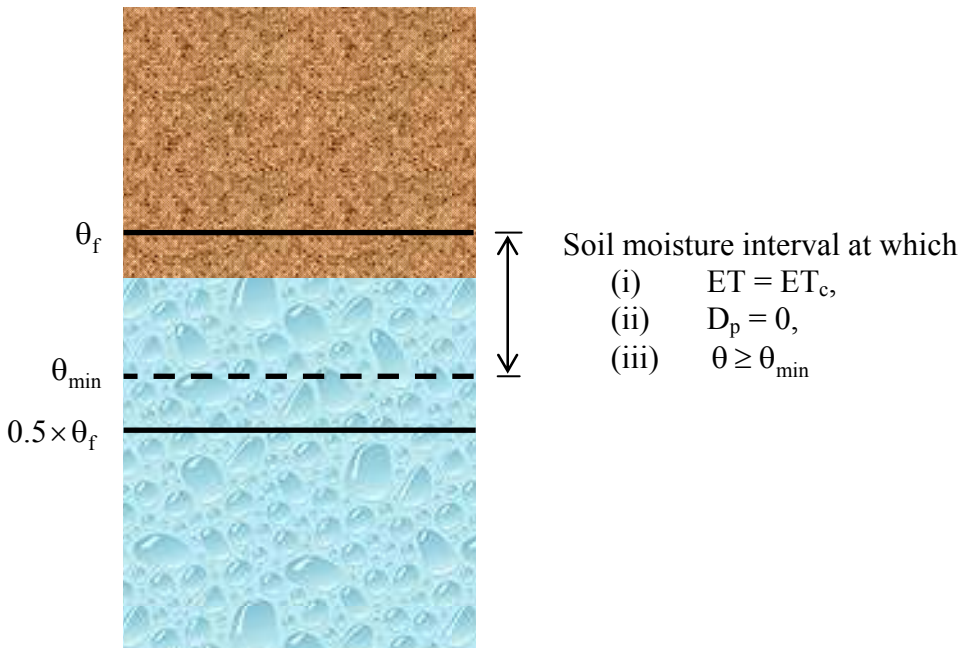


**Figure 3** A schematic representation of the root zone profile

where

$D_r$ = thickness of root zone, (L);

$\theta_{min}^{t+1}$ = minimum soil moisture requirement specified at the end of time step, (L/L);

$\theta_r^t$ = soil moisture that is available in the storage at the beginning of time step assuming that $CU_{AW}$ in the previous time steps were met, (L/L);

$I_{f_p}$ = infiltration of precipitation, (L/T);

$CU_{AW}$ = consumptive use of applied water, i.e. rate of application water required for optimum agricultural conditions, (L/T);

$ET_c$ = evapotranspiration rate under standard conditions, (L/T);

$\Delta t$ = length of time step, (T);

t = counter for time step, (dimensionless).

When soil moisture is at $\theta_{min}$, the ET rate will be equal to $ET_c$ rate and the deep percolation will be zero (Figure 3). These conditions are reflected in equation (21). Solving (21) for $CU_{AW}^{t+1}$, one obtains the rate of applied water required for optimum agricultural conditions:

$$CU_{AW}^{t+1} = \frac{D_r \theta_{min}^{t+1} + ET_c^{t+1} \Delta t - \left( D_r \theta_r^t + I_{f_p}^{t+1} \Delta t \right)}{\Delta t} \geq 0 \qquad (22)$$

Equation (22) guarantees that deep percolation will be zero. Therefore, a portion of $CU_{AW}^{t+1}$ will be used to meet the ET requirements ($ET_c$ in equation (22)) and the rest of it will increase the soil moisture content in the root zone that will be used to meet the ET requirements in future time steps.

Equation (22) represents the amount of moisture that should be added to the root zone for optimum agricultural conditions as described earlier in this section. In general, the performance of the irrigation systems is not 100%. The method of irrigation (e.g. furrow irrigation, sprinkler irrigation, drip irrigation), the irrigation management (scheduling of irrigation events), physical properties of the soil and the climatic conditions during an irrigation event prevent the irrigation water to contribute to the $CU_{AW}$ completely. A portion of the irrigation water almost always becomes deep percolation or return flow. On the other hand, capturing the irrigation water that does not effectively contribute to the $CU_{AW}$ (i.e. losses due to the deep percolation or return flow)

and re-using it increases the overall performance of the irrigation system. Therefore, it is necessary to take the performance of the irrigation systems into account for the computation of the true agricultural water demand.

To compute the agricultural water demand for a crop, IDC uses the seasonal crop application efficiencies. Seasonal crop application efficiency is an indicator of the performance of the irrigation system. It is defined by the user for each crop as a time series input data. With CUAW computed in equation (22) and seasonal crop application efficiency defined by the user, IDC computes the agricultural water requirement as

$$D_{ag}^{t+1} = \frac{CU_{AW}^{t+1}}{Eff^{t+1}} \tag{23}$$

where

$D_{ag}$ = agricultural water demand, (L/T);

$Eff^{t+1}$ = seasonal application efficiency, (dimensionless).

A detailed discussion of the seasonal crop application efficiency is given in the following section.

### 3.1.1. Seasonal Crop Application Efficiency

Seasonal crop application efficiency is a measure for the irrigation performance. Irrigation performance measures are defined in terms of the ultimate use of the applied irrigation water. Burt, et al. (1997) classify the irrigation water use (e.g. consumptive versus non-consumptive, beneficial versus non-beneficial, etc.) and identify several irrigation performance measures; namely irrigation consumptive use coefficient, irrigation efficiency, irrigation sagacity, distribution uniformity, application efficiency

and potential application efficiency. In this document only the irrigation consumptive use coefficient and the irrigation efficiency will be explained as they pertain to the implementation of seasonal crop application efficiency in IDC. A detailed description of all the irrigation performance measures along with the classification of irrigation water use (i.e. consumptive – non-consumptive, beneficial – non-beneficial, and reasonable – unreasonable uses) can be found in Burt, et al. (1997).

#### *3.1.1.a. Irrigation Consumptive Use Coefficient*

The irrigation consumptive use coefficient is defined as the fraction of the irrigation applied water that goes to the consumptive uses (Burt, et al., 1997):

$$\mathrm{ICUC} = \frac{\mathrm{C}}{\mathrm{AW}} \tag{24}$$

where

ICUC = irrigation consumptive use coefficient, (dimensionless);

C = irrigation water that goes to consumptive use, (L/T);

AW = irrigation water, (L/T).

The consumptive use of irrigation water, C, includes the water that ends up in the atmosphere through evaporation or evapotranspiration, and the water that is held in the plant tissues. It should be noted that C in equation (24) is different than the $CU_{AW}$ in equation (22) in that C includes consumptive use of non-agricultural plants whereas $CU_{AW}$ is strictly the consumptive use of the agricultural plants. The fraction of the irrigation water that goes to consumptive use is considered to be irrecoverable. Return flows, deep percolation and losses in the conveyance structures of the irrigation system

are considered to be the part of the irrigation water that goes to non-consumptive uses. Some or the entire non-consumptive portion of the irrigation water may be captured and re-used.

#### *3.1.1.b. Irrigation Efficiency*

Irrigation efficiency is defined as the fraction of the applied irrigation water that is used beneficially:

$$IE = \frac{B}{AW} \tag{25}$$

where

IE = irrigation efficiency, (dimensionless);

B = portion of the applied water that is used beneficially, (L/T).

The beneficial use of irrigation water includes the consumptive use of agricultural crops (i.e. $CU_{AW}$ as defined in equation (22)), and the return flow that are generated due to the irrigation water that is applied to remove salts from agricultural fields.

In IDC, the non-beneficial consumptive use that appear in the expression for the ICUC (see equation (24)) and the beneficial use of irrigation water in terms of return flow that appear in the definition of IE (see equation (25)) are not considered. Therefore, ICUC and IE represent the same irrigation performance measure in the context of IDC (i.e. the fraction of the irrigation water that goes to the beneficial consumptive use of harvested plants) and it is referred to as the seasonal crop application efficiency to avoid any confusion with ICUC and IE. Seasonal crop application efficiency is a value between 0 (zero) and 1. At a given time step t, it can be expressed as

$$Eff^t = \frac{CU^t_{AW}}{AW^t} \tag{26}$$

where

Eff = seasonal crop application efficiency, (dimensionless).

Equation (26) reveals that the application efficiency at a given time step is the ratio of the total irrigation amount less system loses (return flow and deep percolation) to the total amount of irrigation water. At a given time step, it is likely that simulated seasonal crop application efficiencies computed from equation (26) will not be equal to the application efficiencies specified by the user as input to IDC. However, it is expected that the average of the simulated application efficiencies over a long period of time (e.g. over an irrigation season) should converge to the values computed based on the user-specified input parameters.

### 3.1.2. Re-use of Irrigation Water

Some or all of the irrigation water that contributes to deep percolation or return flow can be captured in an irrigation unit and re-used (i.e. re-applied) at the same unit or at a downstream unit. An irrigation unit can be a single farm, a collection of farms such as an irrigation district, or a collection of irrigation districts (Solomon and Davidoff, 1999).

Re-use of irrigation water can improve irrigation efficiency (i.e. seasonal crop application efficiency as implemented in IDC) and downstream water quality, reduce irrigation labor, and conserve soil and nutrient resources. It also enables irrigators to meet surface water discharge restrictions (ASAE, 1999).

For an irrigation unit, the re-use factor can be expressed in terms of the re-used deep percolation and re-used return flow (Solomon and Davidoff, 1999):

$$\rho = \frac{\mu D_p + \tau R_f}{D_p + R_f} \tag{27}$$

where

$\rho$ = irrigation water re-use factor, (dimensionless);

$D_p$ = deep percolation, (L/T);

$R_f$ = return flow, (L/T);

$\mu$ = fraction of the deep percolation that is captured and re-used, (dimensionless);

$\tau$ = fraction of return flow that is captured and re-used, (dimensionless).

As stated earlier, re-use of irrigation water increases overall irrigation efficiency. To derive the expression for the seasonal crop application efficiency that takes the re-use factor into account, one can re-write equation (26) as follows:

$$Eff_r = \frac{CU_{AW}}{AW} = \frac{CU_{AW}}{CU_{AW} + D_p^c + R_f^c} \tag{28}$$

where

$Eff_r$ = seasonal crop application efficiency after re-use of irrigation water, (dimensionless);

$D_p^c$ = deep percolation that is not re-used, (L/T);

$R_f^c$ = return flow that is not re-used, (L/T).

The time step index, t, is dropped in (28) for the sake of simplicity. Equation (28) can be re-expressed in terms of the re-use factor:

$$\mathrm{Eff_r} = \frac{\mathrm{CU_{AW}}}{\mathrm{CU_{AW}} + (1-\rho)\left(\mathrm{D_p} + \mathrm{R_f}\right)} \tag{29}$$

After dividing the numerator and denominator of (29) by the total applied water, AW, and rearranging, one obtains

$$\mathrm{Eff_r} = \frac{\mathrm{Eff}}{1-\rho\left(1-\mathrm{Eff}\right)} \tag{30}$$

Equation (30) shows the effect of capturing and re-using the losses from irrigation water on the seasonal application efficiency. When there is no re-use, i.e. $\rho = 0$, then Eff and $\mathrm{Eff_r}$ are equal. Using the modified seasonal application efficiency, $\mathrm{Eff_r}$, in equation (23) to express the agricultural water demand, one obtains

$$\mathrm{D}^{t+1} = \frac{\mathrm{CU_{AW}^{t+1}}}{\mathrm{Eff_r^{t+1}}} = \frac{\mathrm{CU_{AW}^{t+1}}}{\mathrm{Eff}^{t+1}}\left[1-\rho^{t+1}\left(1-\mathrm{Eff}^{t+1}\right)\right]$$

$$= \frac{\mathrm{CU_{AW}^{t+1}}}{\mathrm{Eff}^{t+1}} - \rho^{t+1}\mathrm{CU_{AW}^{t+1}}\frac{1-\mathrm{Eff}^{t+1}}{\mathrm{Eff}^{t+1}} \tag{31}$$

Comparing equations (23) and (31), it can be seen that re-use of irrigation water decreases the amount of "prime" water that needs to be applied to the irrigation unit. In the case of no re-use, i.e. $\rho = 0$, equation (23) is equivalent to (31).

$\rho$ in equation (31) is a time-series input parameter specified for each crop in IDC. Treating $\rho$ as a time-dependent parameter allows the modeler to simulate changing irrigation systems over the simulation period (e.g. switching from a less re-use oriented

system to a more re-use oriented one). In IDC, only the re-use of return flow is considered. This means that, μ, the fraction of the deep percolation that is captured and re-used is assumed to be zero at all times.

It is important to note that ρ in equation (27) represents the fraction of the non-consumed water that is re-used. Sometimes, the re-use factors used by irrigation practitioners refer to the fraction of total applied water, AW, that is re-used (DWR, 1994; Zapata, et al., 2000):

$$\rho^* = \frac{\rho\left(D_p + R_f\right)}{AW} = \frac{\rho\left(D_p + R_f\right)}{CU_{AW} + D_p + R_f} \tag{32}$$

In this case a conversion method can be used to convert ρ* into ρ. Substituting AW – $CU_{AW}$ instead of the losses (i.e. $D_p + R_f$), dividing the numerator and the denominator by AW and rearranging, (32) becomes

$$\rho^* = \frac{\rho\left(1 - \frac{CU_{AW}}{AW}\right)}{\frac{CU_{AW}}{AW} + (1-\rho)\left(1 - \frac{CU_{AW}}{AW}\right)}$$

$$= \frac{\rho\left(1 - Eff_{sa,avg}\right)}{1 - \rho\left(1 - Eff_{sa,avg}\right)} \tag{33}$$

Equation (33) can be re-arranged to express ρ in terms of ρ*:

$$\rho = \frac{\rho^*}{(1 - Eff)(1 + \rho^*)} \tag{34}$$

In practice it is not always easy to quantify CUAW, deep percolation, return flow and actual amount of losses that is re-used. These values are sometimes grossly

estimated leading to inconsistent values for seasonal crop application efficiency and re-use factor. In such a case, if equation (34) is used to convert ρ* into ρ, the following inequality should be checked:

$$\mathrm{Eff}\left(1+\rho^{*}\right) \leq 1 \tag{35}$$

Inequality (35) guarantees that when equation (34) is used with grossly estimated efficiency and re-use factors, ρ will not be computed as a value larger than 1 violating its physical meaning.

# 4. IDC Input and Output Data

## 4.1. Input Parameters

### 4.1.1. Parameters Related to Execution Control

i) Starting date and time of simulation

ii) Ending date and time of simulation

iii) Length of simulation time step

### 4.1.2. Subregional Parameters

i) Number of subregions

ii) Subregion names

### 4.1.3. Crop Parameters

i) Number of modeled crops (2 additional land use types, urban and native vegetation lands, are added to this number internally)

ii) Crop codes to be used during print-out of the results

iii) Area of each crop (including urban and native vegetation) in each subregion

iv) Rooting depths (including urban and native vegetation)

v) Minimum soil moisture requirement as a time series data for each subregion-agricultural crop combination

vi) Seasonal crop irrigation efficiencies as a time series data for each subregion-agricultural crop combination

vii) $ET_c$ rates as a time series data for each subregion-crop combination (including urban, native vegetation and bare soil)

#### 4.1.4. Soil Parameters

i) Flag to indicate if physically-based method (requires saturated hydraulic conductivity) or the deep percolation fractions will be used for the computation of deep percolation

ii) Field capacity for each subregion-crop combination (including urban and native vegetation)

iii) Total porosity for each subregion-crop combination (including urban and native vegetation)

iv) Saturated hydraulic conductivity or deep percolation fraction, depending on the value of flag listed above, for each subregion-crop combination (including urban and native vegetation)

v) SCS curve number for each subregion-crop combination (including urban and native vegetation)

### 4.1.5. Parameters Related to Water Management

i) Fraction of pervious urban area to total urban area in each subregion

ii) Re-use factors as time series data for each subregion-agricultural crop combination as well as for urban lands in each subregion

iii) Destination for urban surface runoff (groundwater or stream)

iv) Fraction of total urban water that is used indoors as time series data for each subregion

v) Urban water demand as time series data for each subregion

### 4.1.6. Parameters Related to Precipitation

i) Precipitation time series data for each subregion-crop combination (including urban and native vegetation)

ii) Flag to indicate if the infiltration of precipitation will be computed or if it will be read in from a file

iii) Infiltration of precipitation, depending on the value of the flag listed above, for each subregion-crop combination (including urban and native vegetation)

### 4.1.7. Parameters Related to Simulation Output

i) Conversion factors and units for the simulation output values

ii) Pathnames to be used in storing time series simulation results in the output DSS file

## 4.2. Output Data

### 4.2.1. Standard Output Data

i) Agricultural water supply requirement for each crop in each subregion

ii) Total agricultural water supply requirements for each subregion

iii) Return flow for each agricultural crop as well as urban lands in each subregion

iv) Total agricultural return flow for each subregion

v) Precipitation runoff for each agricultural crop as well as urban and native vegetation lands in each subregion

vi) Total precipitation runoff for agricultural lands (combined runoff from individual crops) in each subregion

vii) Deep percolation for each agricultural crop as well as urban and native vegetation lands in each subregion

viii) Total deep percolation for agricultural lands (combined deep percolation from individual crops) in each subregion

### 4.2.2. Optional Root Zone Water Budget Output Data

i) Area of each agricultural crop as well as urban and native vegetation lands in each subregion

ii) Precipitation over each agricultural crop as well as urban and native vegetation lands in each subregion

iii) Precipitation runoff from each agricultural crop as well as urban and native vegetation lands in each subregion

iv) Precipitation over each agricultural crop as well as urban and native vegetation lands in each subregion

v) Prime applied water (i.e. before any re-use takes place) over each agricultural crop as well as urban and native vegetation lands in each subregion; it is automatically set to zero for native vegetation lands

vi) Re-used water for each agricultural crop as well as urban and native vegetation lands in each subregion; it is automatically set to zero for native vegetation lands

vii) Total applied water (i.e. total of prime applied and re-used water; it is equal to the water supply requirement computed in IDC) for each agricultural crop as well as urban and native vegetation lands in each subregion; it is automatically set to zero for native vegetation lands

viii) Return flow of applied water for each agricultural crop as well as urban and native vegetation lands in each subregion; it is automatically set to zero for native vegetation lands

ix) Moisture storage at the beginning of each time step for each agricultural crop as well as urban and native vegetation lands in each subregion

x) Total infiltration (equivalent to the summation of precipitation and prime applied water less precipitation runoff and applied water return flow) for each agricultural crop as well as urban and native vegetation lands in each subregion

xi) Evapotranspiration for each agricultural crop as well as urban and native vegetation lands in each subregion

xii) Deep percolation for each agricultural crop as well as urban and native vegetation lands in each subregion

xiii) Moisture storage at the end of each time step for each agricultural crop as well as urban and native vegetation lands in each subregion

### 4.2.3. Optional Potential $CU_{AW}$ Output Data

i) Potential $CU_{AW}$ (crop water demand assuming 100% seasonal crop application efficiency) computed by IDC for each agricultural crop in each subregion

ii) Total potential $CU_{AW}$ (combined potential $CU_{AW}$ for each crop) for each subregion

# 5. Differences between IDC and CU Model

IDC is created to replace CU model in developing hydrologic fluxes for CalSim studies. CU model has been used for many years for this purpose. To compare CalSim studies that use IDC-generated fluxes versus CU-model-generated fluxes, it is imperative to study and document the sources of differences between CU model results and IDC

results. This section lists the sources of differences between the two models. In some cases, it was necessary to setup a simple problem and simulate the fluxes using both IDC and CU model to identify these sources. Appendix A lists the problem settings for cases where a simplified example problem is used.

Following is a list of identified sources for the differences between results of IDC and CU model:

1. IDC enforces three criteria when computing the crop demand. One of these criteria is that soil moisture levels should at all times be maintained above half of field capacity. This is because, unlike CU model, when soil moisture falls below half of field capacity the plants are considered to be stressed. To avoid this situation IDC takes half of field capacity as target moisture instead of minimum moisture as input by user. Consequently, this raises the water demand. This difference is demonstrated in Figure 4 through October demands.
2. CU model maintains the soil moisture at minimum during non-irrigation months even if there is no precipitation (hypothetical case as shown in Figure 4). On the other hand, IDC allows the depletion of storage below minimum soil moisture through ET to maintain the mass balance. This will cause IDC to compute a larger demand in the following irrigation month. This is demonstrated in Figure 4 through March demands.
3. Round off errors sometimes cause noticeable differences when volumetric values are compared for crops with large acreages. For example 0.04 inch difference (due to round off errors) in the soil moisture for a crop with 80

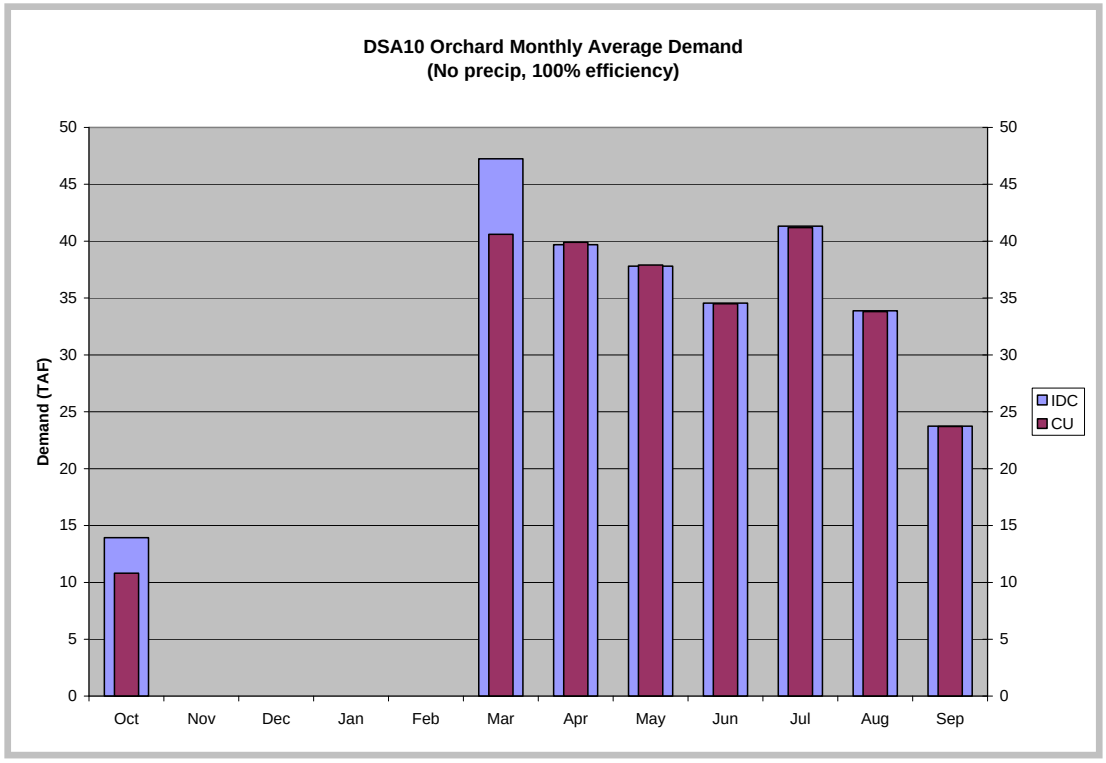


**Figure 4** Results of the first test problem (see Appendix A for the settings used in creation of this chart)

TAC area generates 0.266 TAF error. This is demonstrated in Figure 4 by April demands. The small differences between demand computed by IDC and CU model in Figure 1 for May, June, July and August are all due to round-off errors.

4. Notice the demand pattern in Figure 4 in the absence of precipitation. Both CU model and IDC show an unexpected pattern. There is a large demand in March, decreasing until June. Then the demand spikes up in July and decreases again until October. Although this is a hypothetical situation, it helps to see the effect of precipitation on the demand pattern and how it shapes this pattern into one that people expect to see; i.e. small

or no demand in winter months and increasing demand in summer months. This point is made because when the demand pattern in IDC show unexpected behavior (e.g. no demand in June in one of the simulation years), the cause can be tracked to the precipitation pattern in most cases. Figure 5 shows how components of total demand ($ET_c$ and minimum soil moisture requirement) and source of moisture to meet this total demand (effective precipitation and available soil moisture) shape the pattern of demand for applied water.

5. It has been noted that IDC uses half of field capacity as the end-of-month moisture target if the minimum soil moisture is less than half of field

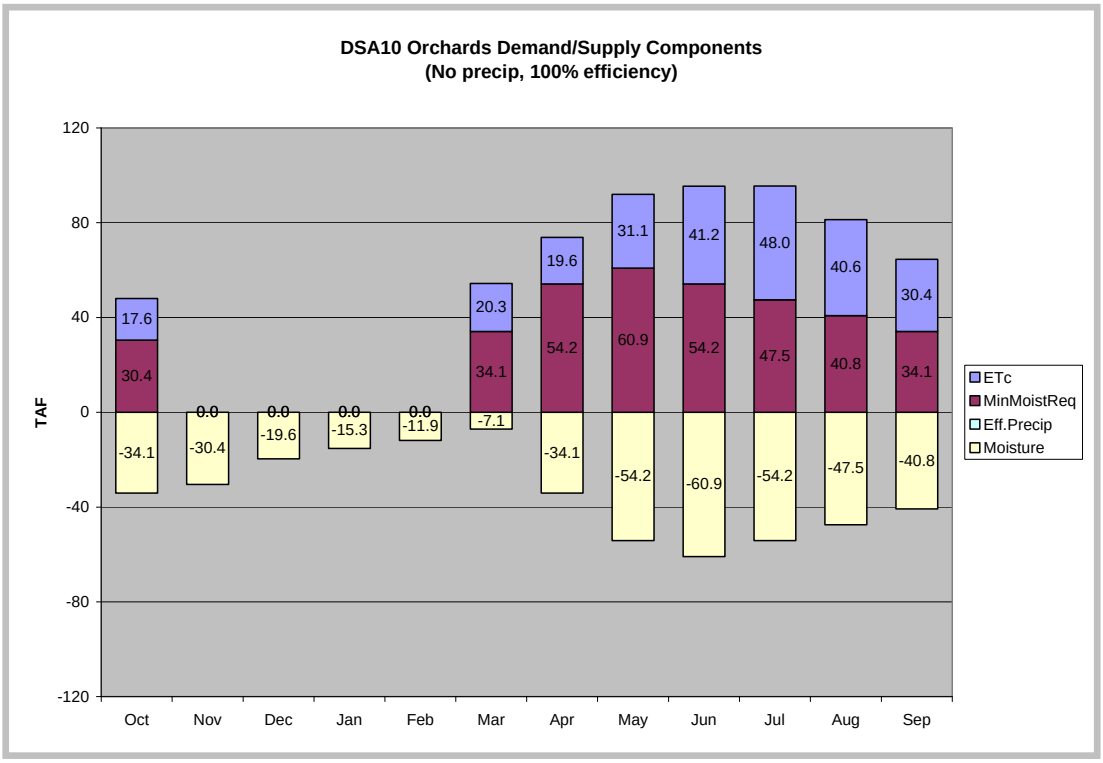


**Figure 5** Inflow and outflow fluxes in IDC for the first test problem

capacity. In a case where the effective rainfall is the same between IDC and CU model, this creates a difference in computed demands as depicted in March of Figure 6. In October, IDC sets the end-of-month moisture target to a value greater than CU model (IDC sets it to half of field capacity whereas CU model sets it to minimum soil moisture). This generates a larger computed demand in the case of IDC. This difference is more or less carried through non-irrigation months (November through February in Figure 6). In March, the end-of-month moisture target is the same for both IDC and CU model. However, since IDC has been maintaining a larger moisture storage up to this point (due to October

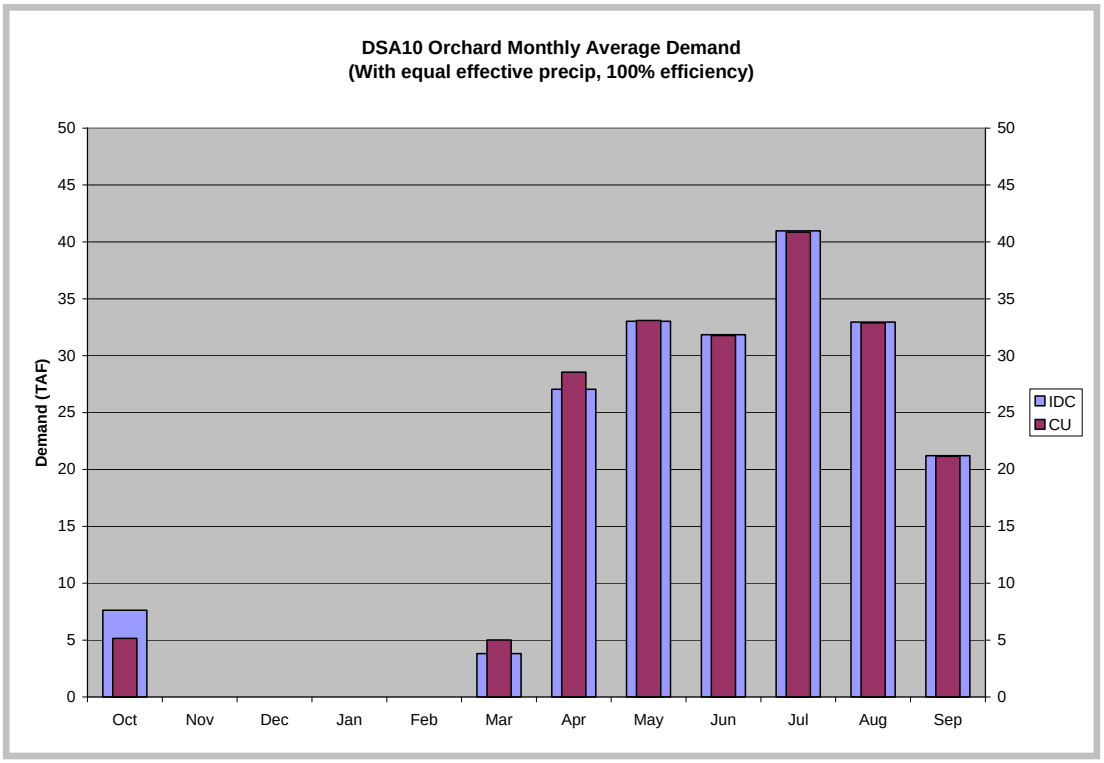


**Figure 6** Results of the second test problem (see Appendix A for assumptions used in creation of this chart)

demands), the demand computed by IDC in March is less than that computed by CU model (Figure 6). The monthly average components that are used in computing applied water demand in IDC are shown in Figure 7.

6. In Figure 6, the average October demand computed by IDC is 0.34 inches higher than that computed by CU model. On the other hand, the average March demand computed by CU model is 0.18 inches higher than that computed by IDC. Based on the previous discussion, one expects to see the same difference between CU model and IDC for October and March; i.e. 0.34-inch difference in IDC's favor in October should be met by a

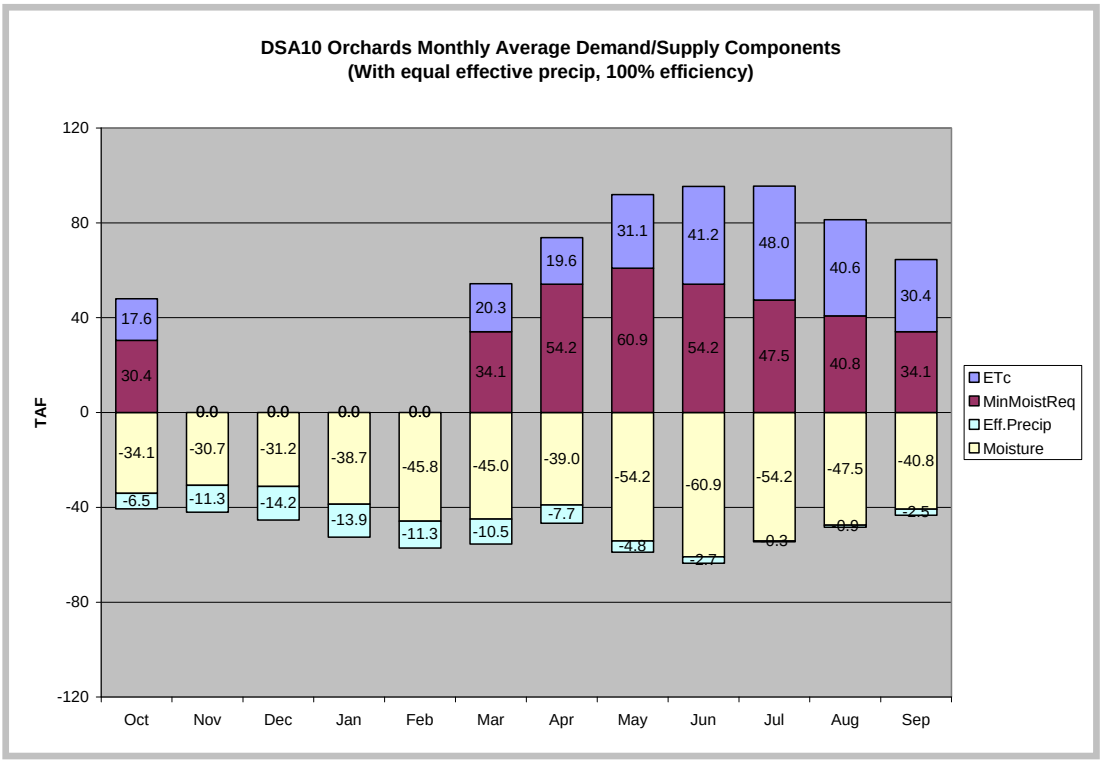


**Figure 7** Inflow and outflow fluxes in IDC for the second test problem

0.34-inch difference in CU model's favor in March. This does not occur because, in the case of moisture shortage, IDC decreases the actual ET. If the moisture falls below half of field capacity IDC computes an ET value that is less than the potential ET. This means that the moisture storage is not depleted as much as the potential ET, and in March, CU model requires less water to catch up with the moisture content computed by IDC.

7. In Figure 6, average April demands also show a difference. This is because, in some years, there is enough precipitation in March that the demands computed by CU model and IDC are zero, and end-of month storages in March are higher than the minimum soil moisture requirement. This means that the difference in the demands generated in October is now carried beyond March (as described in the above section), into April. Now, CU model catches up with IDC soil moisture in April rather than in March by computing a larger demand.

8. CU model assumes that the entire precipitation is available for consumptive use. IDC, on the other hand, computes runoff which decreases the precipitation that is available for consumptive use. This leads to IDC computing a larger demand compared to CU model. This behavior can be seen in months with observed precipitation (March, April, May, June, September) in Figure 8. The larger the precipitation the larger the difference between the demands computed by IDC and CU model.

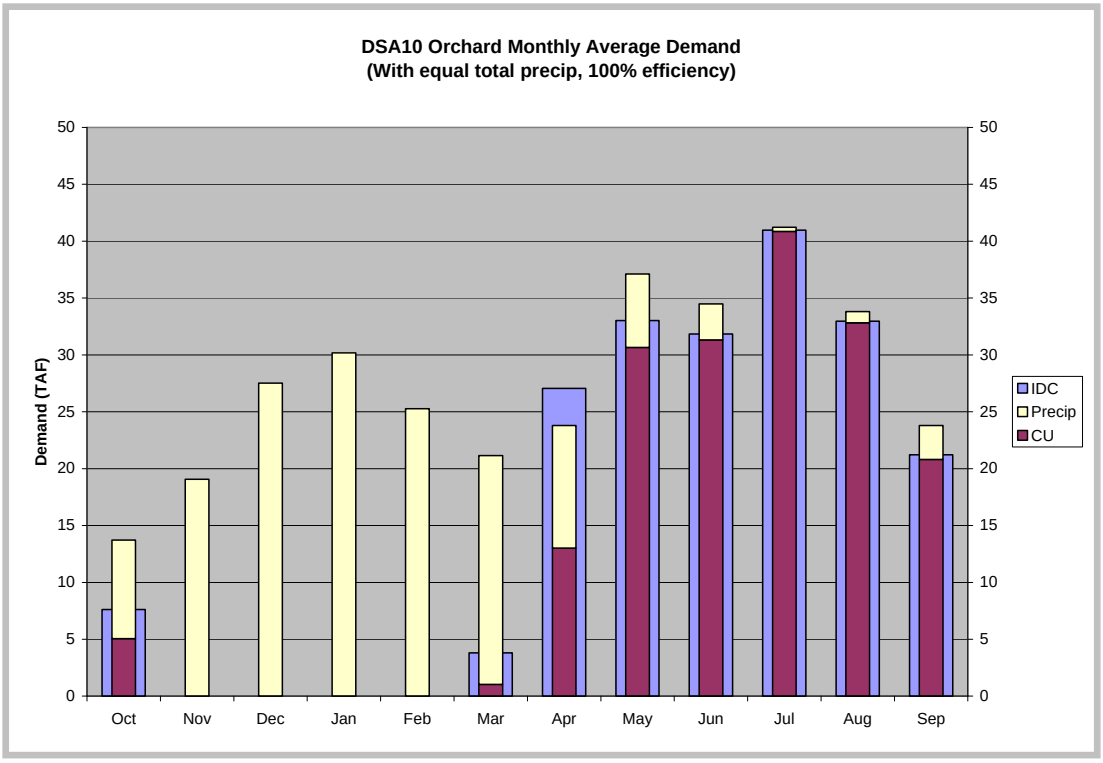


**Figure 8** Results for the third test problem (see Appendix A for assumptions used in creation of this chart)

# 6. Appendix A

## 6.1. Generation of Figure 4

This figure was generated by running IDC and CU model with following settings:

i) All crop areas except for orchards were zeroed out. Orchard acreage was set to 81140 acres.

ii) Deep percolation in IDC was turned off.

iii) Precipitation was turned off in both IDC and CU model.

iv) The irrigation efficiency was set to 100% and re-use factor was set to zero in IDC.

v) The percent loss in CU model was set to zero.

## 6.2. Generation of Figure 6

This figure was generated by running IDC and CU model with following settings:

i) All crop areas except for orchards were zeroed out. Orchard acreage was set to 81140 acres.

ii) Deep percolation in IDC was turned off.

iii) Precipitation in CU model was set equal to infiltration of precipitation that is computed in IDC.

iv) The irrigation efficiency was set to 100% and re-use factor was set to zero in IDC.

v) The percent loss in CU model was set to zero.

## 6.3. Generation of Figure 8

This figure was generated by running IDC and CU model with following settings:

i) All crop areas except for orchards were zeroed out. Orchard acreage was set to 81140 acres.

ii) Deep percolation in IDC was turned off.

iii) Precipitation in CU model was set equal to precipitation used in IDC.

iv) The irrigation efficiency was set to 100% and re-use factor was set to zero in IDC.

v) The percent loss in CU model was set to zero.

## 7. References


Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. 1998. *Crop evapotranspiration: guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56, Rome.

ASAE. 1999. *ASAE Standards, EP408.2 DEC99: Surface irrigation runoff reuse systems, 912-915.* St. Joseph, Michigan.

Burt, C. M., Clemmens, A. J., Strelkoff, T. S., Solomon, K. H., Bliesner, R. D., Hardy, L. A. and Howell, T. A. 1997. Irrigation performance measures: Efficiency and uniformity. *J. Irrig. Drain. E.-ASCE*, 123(6), 423-442.

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

DWR. 1994. *Central Valley Production Model - Supporting documentation and data*. Department of Water Resources, Sacramento, California.

DWR. 2007. *Integrated Water Flow Model (IWFM v3.0): Theoretical documentation*. Hydrology Development Unit, Modeling Support Branch, Bay-Delta Office, Sacramento.

Rawls, W. J., Brakensiek, D. L., and Saxton, K. E. 1982. Estimation of soil properties. *Transactions of the American Society of Civil Engineers,* 1316-1320.

Schroeder, P. R., Dozier, T. S., Zappi, P. A., McEnroe, B. M., Sjostrom, J. W., and Peton, R. L. 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.

Schultz, E .F. 1974. *Problems in applied hydrology.* Water Resources Publications, Fort Collins, CO.

Solomon, K. H. and Davidoff, B. 1999. Relating unit and sub-unit performance. *T. ASAE*, 42(1), 115-122.

USDA, Soil Conservation Service. 1985. *National engineering handbook, section 4, hydrology, chapter 9 and 10.* US Government Printing Office, Washington, D.C.

Zapata, N., Playan, E. and Faci, J. M. 2000. Water reuse in sequential basin irrigation. *J. Irrig. Drain. E.-ASCE*, 126(6), 362-370.