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# WaSim
# Technical Manual

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**List of variables**

| Symbol | Description | Units |
|---|---|---|
| $\alpha$ | soil evaporation constant, mm $d^{-½}$ | mm $d^{-½}$ |
| $\tau$ | drainage coefficient | dimensionless |
| $\theta$ | volume water fraction | dimensionless |
| $\phi$ | ditch water level or drain diameter | m |
| $\mu$ | drainable porosity | dimensionless |
| $_{\Delta r}$ | daily root growth | m $d^{-1}$ |
| $\theta_{SAT}$ | volume water fraction at saturation | dimensionless |
| a | empirical constant | dimensionless |
| b | empirical constant | dimensionless |
| bs | reduction in yield due to salinity | % $(dS\ m^{-1})^{-1}$ |
| B | bare soil fraction | dimensionless |
| c | empirical constant | $m^{-1}$ |
| C | crop cover fraction | dimensionless |
| d | Hooghoudt's equivalent depth | m |
| $d_0$ | depth from the drain to the impermeable layer | m |
| e | the potential contribution of groundwater to ET | mm $d^{-1}$ |
| EC | electrical conductivity of soil water | dS $m^{-1}$ |
| $EC_I$ | electrical conductivity of irrigation water | dS $m^{-1}$ |
| ECs | electrical conductivity of saturation extract | dS $m^{-1}$ |
| ECs' | Threshold electrical conductivity of saturation extract | dS $m^{-1}$ |
| Egw | contribution from water table to soil evaporation | mm $d^{-1}$ |
| Em | evaporation from mulch cover | mm $d^{-1}$ |
| Eo | open water evaporation | mm |
| Es | soil evaporation | mm $d^{-1}$ |
| $Es_o$ | potential soil evaporation | mm $d^{-1}$ |
| ET | actual evapotranspiration | mm $d^{-1}$ |
| $ET_o$ | reference evapotranspiration | mm $d^{-1}$ |
| f | fraction of drain flow from below drain depth | dimensionless |
| FC | water content of root zone at field capacity | mm |
| $\theta_{FC}$ | volume water fraction at field capacity | dimensionless |
| $f_s$ | relative saturation | dimensionless |
| h | height of the mid-drain water table above the drain depth | m |
| I | irrigation water applied | mm $d^{-1}$ |
| Ie | effective irrigation water applied | mm $d^{-1}$ |
| K | saturated hydraulic conductivity | mm $d^{-1}$ |
| $Kc_{max}$ | ratio of potential transpiration to reference evapotranspiration at full cover | dimensionless |
| Kp | open water evaporation (pan) coefficient | dimensionless |
| Ks | transpiration reduction factor for salinity | dimensionless |
| Ky | yield response factor due to water stress | dimensionless |
| L | drain spacing | m |
| Le | leaching efficiency | dimensionless |
| M | fraction mulch cover | dimensionless |

| | | |
|---|---|---|
| $M_0$ | cover fraction of mulch at planting | dimensionless |
| n | duration of root growth | d |
| N | Curve number | dimensionless |
| $N_1$ | Curve number for dry antecedent conditions | dimensionless |
| $N_2$ | Curve number for average antecedent conditions | dimensionless |
| $N_3$ | Curve number for wet antecedent conditions | dimensionless |
| p | fraction of total available water that is easily available | dimensionless |
| P | gross rainfall | mm $d^{-1}$ |
| P’ | available precipitation | mm $d^{-1}$ |
| $P_e$ | effective rainfall | mm $d^{-1}$ |
| Pond | ponding depth | mm |
| Pond’ | maximum allowable ponding depth | mm |
| PWP | water content of root zone at permanent wilting point | mm |
| Q | drain flow | mm $d^{-1}$ |
| q | drainage from compartment | mm $d^{-1}$ |
| Q’ | fraction of drain flow from below drain depth | dimensionless |
| $q_s$ | daily addition to water table from canal seepage | mm $d^{-1}$ |
| R | surface runoff | mm $d^{-1}$ |
| r | root depth | m |
| $r_0$ | planting depth | m |
| $r_{max}$ | maximum root depth | m |
| s | maximum storage | mm |
| S | mass of salt | mm dS $m^{-1}$ $d^{-1}$ |
| Sd | mass of salt in the water leaving compartment j | mm dS $m^{-1}$ $d^{-1}$ |
| $S_I$ | mass of salt added by irrigation water | mm dS $m^{-1}$ $d^{-1}$ |
| SWD | soil water deficit of root zone | mm |
| t | time since the start of stage 2 | d |
| Ta | actual transpiration | mm $d^{-1}$ |
| TAWC | total available water capacity of root zone | mm |
| Tgw | contribution from water table to transpiration | mm $d^{-1}$ |
| To | potential transpiration | mm $d^{-1}$ |
| $t_p$ | time since planting | d |
| U | maximum cumulative evaporation | mm $d^{-1}$ |
| Vs | net flux from the water table to the root zone | mm $d^{-1}$ |
| W | water content | mm |
| z | compartment thickness | mm |
| $z_w$ | depth to the water table | m |
| $\beta$ | exponent dependant on depth to the impermeable layer | $m^{-1}$ |

# 1. THE WATER BALANCE MODEL

The model carries out a one-dimensional, daily, soil water balance. It aims to simulate the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to climate, irrigation, and canal seepage where relevant.

The upper boundary is the soil surface and the lower boundary is the impermeable layer[1]. Water is stored between these two boundaries in five stores (compartment):

- Compartment 0. The surface (0 – 0.15m) layer,
- Compartment 1. The active root zone (0.15m – root depth),
- Compartment 2. The unsaturated compartment below the root zone (root depth – water table),
- Compartment 3. The saturated compartment above drain depth (water table – drain depth),
- Compartment 4. The saturated compartment below drain depth (drain depth – impermeable layer).

The boundary between compartments 1 and 2 will change as the roots grow. Before plant roots reach 0.15m, compartment 1 will have zero thickness. Similarly the boundary between compartments 2 and 3 will fluctuate with the water table.

## 1.1 Inputs of water

Inputs of water are from net rainfall, net irrigation and lateral seepage, where relevant. Net rainfall and irrigation are defined as the gross amounts, less interception losses, and surface runoff. Irrigation may, or may not, be subject to interception, depending on the application method.

## 1.2 Outputs of water

The outputs of water from the profile are;

1. Open water evaporation, *Eo*, occurs only if there is ponding on the soil surface. In this case, there is no transpiration.
2. Soil evaporation, *Es*occurs from compartment 0 only.
3. Plant transpiration, $Ts_0$, $Ts_1$ occurs from compartments 0 and 1.

[1] The model is insensitive to an impermeable layer >10m.

4. Capillary rise from the groundwater. Rather than redistribute water from the water table to the unsaturated compartments and then to evaporation or transpiration, the model simulates a direct 'shortcut' from the groundwater to evaporation, *Egw* and transpiration, *Tgw*.

5. Drain flow occurs from the lower compartments if the water table is above the drain depth. The rate of drain flow is a function of the height of the water table above the drain.

6. Pumped drainage. A constant daily output can be taken directly from the water table. This can be used to simulate pumped drainage.

## 1.3 Redistribution of soil water

Soil water moves from upper compartments to compartments below only when the soil water content of the compartment exceeds field capacity. In this case, the rate of drainage, $q_0$ to $q_2$, is a function of the amount of excess water.

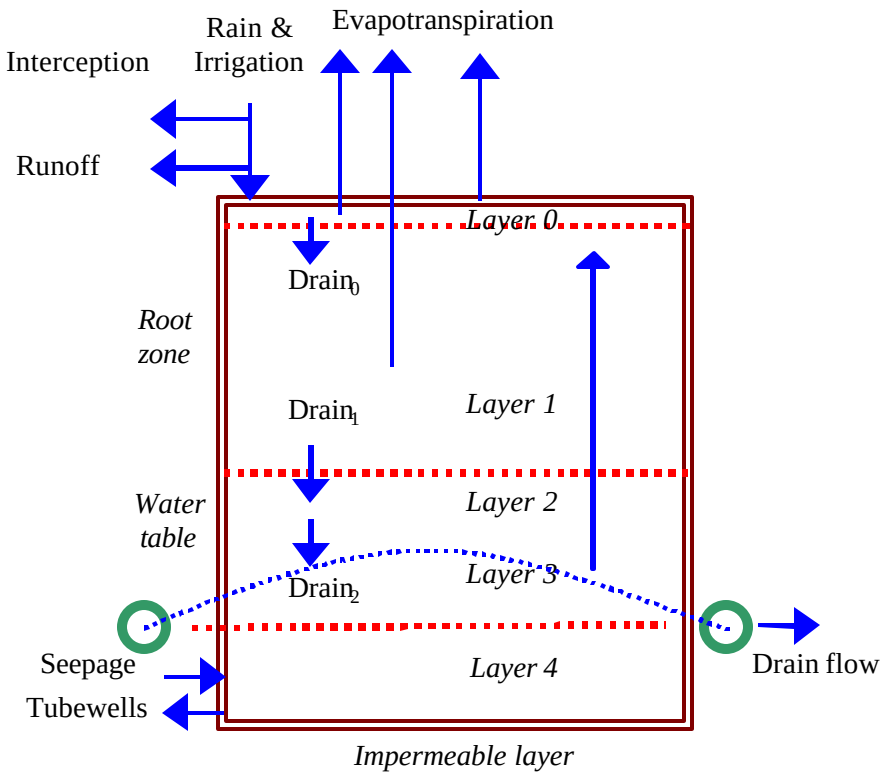



**Figure 1. Overview of the soil water balance**

## 2. SURFACE CONDITIONS

The soil surface is divided into three components – plant cover, bare soil and mulch - and the evapotranspiration from each is modelled separately.

## 2.1 Crop cover fraction

The crop cover fraction on a particular day is determined by linear interpolation between the dates of emergence, 20% cover, maximum cover, maturity and harvest (Figure 2). If the maximum cover fraction is less than 20%, then the first stage is ignored. Senescence is simulated by a linear reduction in crop cover fraction between maximum cover at maturity and zero at harvest.

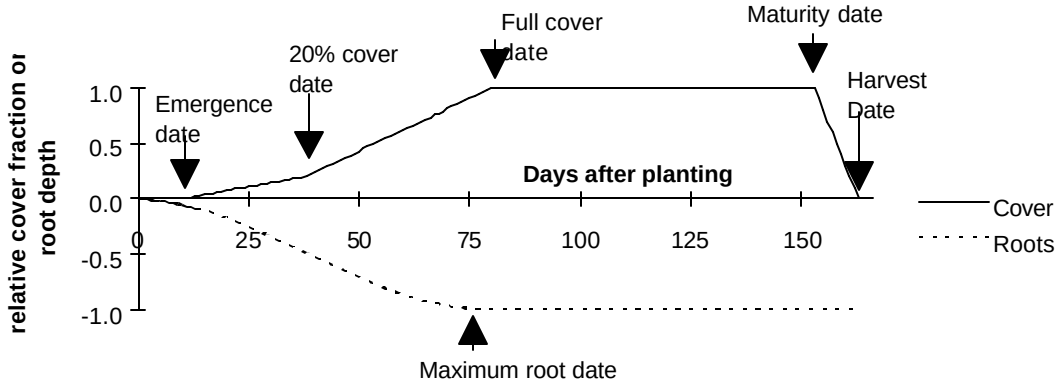



**Figure 2. Crop cover and root depth development**

## 2.2 Mulch cover fraction

The fraction of the ground covered by mulch each day is determined by;

$$M_i = (1 - C_i) M_0 \qquad (1)$$

where

$M_i$ cover fraction of mulch on day i
$M_0$ cover fraction of mulch at planting
$C_i$ cover fraction of crop on day i

i.e. the mulch is assumed to cover the entire surface areas, but $M_0$ reflects the permeability of the mulch.

## 2.3 Bare soil fraction

The fraction of the ground covered by bare soil each day is determined by;

$$B_i = 1 - M_i - C_i \qquad (2)$$

where

$B_i$ bare soil fraction on day i

## 2.4 Ponding

If the water table reaches the soil surface, ponding occurs. Once ponding occurs, the surface is treated as open water and there is no transpiration or soil evaporation loss.

# 3. AVAILABLE WATER AND SOIL WATER DEFICIT

## 3.1 Root depth

The root depth on a particular day is calculated from;

**Table 1 Calculation of root depth**

| Condition | Root depth |
|---|---|
| a) Planting date | $r_0$ |
| b) Planting to maximum root date | $r_{i-1} + \Delta r$ |
| c) Maximum root date to harvest | $r_{max}$ |
| d) After harvest | 0 |

where

$r_i$ root depth on day i, m
$\Delta r$ daily root growth, m
$r_0$ planting depth, m
$r_{max}$ maximum root depth, m

The root growth on a particular day is determined from a sigmoidal root growth curve (Borg and Grimes, 1986)

$$Dr = [0.5 + 0.5 * SIN (3.03 * (t_p / n) - 1.47)] * (r_{max} - r_0) \quad (3)$$

where

$t_p$ time since planting, days
$n$ duration of root growth, days

The root growth is limited by the water table, but is not reduced if a water table rises into an established root zone.

## 3.2 Available water capacity

The total, and easily, available water capacity are calculated each day from;

$$TAWC = FC - PWP \quad (4)$$

$$FC = q_{FC} * r_i * 1000 \quad (5)$$

$$PWP = q_{PWP} * r_i * 1000 \quad (6)$$

$$EAWC = TAWC \; x \; p \quad (7)$$

where

*TAWC* total available water capacity of root zone, mm
EAWC easily available water capacity of root zone, mm
*FC* water content of root zone at field capacity, mm
PWP water content of root zone at permanent wilting point , mm
$\theta_{FC}$ volume water fraction at field capacity
$q_{PWP}$ volume water fraction at permanent wilting point
*p* fraction of total available water that is easily available, dimensionless
$r_i$ root depth on day i, m

All soil parameters are weighted according to the fractions of the root zone in the top soil and subsoil where the physical characteristics may be different.

### 3.3 Root zone deficit

The soil water deficit of the root zone is calculated from:

$$SWD = (q_{FC} - q) * r * 1000 \quad (8)$$

where

*SWD* soil water deficit of root zone, mm
*r* root depth, m
$q_{FC}$ volume water fraction at field capacity, dimensionless
*q* volume water fraction of root zone, dimensionless

## 4. INPUTS

### 4.1 Gross rainfall and irrigation

Gross rainfall on each day is read from the input data file and irrigation may be given, or determined by the model according to scheduling rules. The irrigation plan determines whether irrigation applications are subject to interception loss or not. For example, drip irrigation would not be subject to interception, whereas sprinkler irrigation would.

### 4.2 Interception loss

Net rainfall (or irrigation), i.e. that part not intercepted by the crop canopy and directly evaporated, is estimated from

$$P_n = P\,(1-C) + (a + b\,P)\,C \quad (P > a)$$

$$P_n = P \quad (P \leq a) \quad (9)$$

where

$P_n$ net rainfall, mm

$P$ gross rainfall, mm

$C$ crop cover fraction (dimensionless)

$a$, $b$ empirical constants (dimensionless)

Thus, interception loss = $P$ - $P_n$

## 4.3 Surface runoff

Surface runoff is comprised of two components; runoff due to intense rainfall (infiltration excess) and runoff due to saturated soil. As the rainfall data used to drive the water balance model is only available on a daily timestep, daily surface runoff due to the intensity of rainfall, $R_1$, is estimated using the US SCS Curve Number method,

$$R_1 = \frac{(P - 0.2s)^2}{(P + 0.8s)} \qquad (10)$$

where

$R_1$ surface runoff, mm $d^{-1}$

$P$ gross rainfall, mm $d^{-1}$

$s$ maximum storage for the given antecedent conditions, mm

The maximum storage, $s$, on a particular day is estimated from the storage at dry antecedent conditions, $s_1$, the relative saturation of the top 0.15 m of the soil and two weighting factors, $W_1$ and $W_2$. (Hawkins *et al*., 1985).

$$s = s_1\left(1 - \frac{f_s}{f_s + \exp(W_1 - W_2 f_s)}\right) \qquad (11)$$

$f_s$ relative saturation of the surface compartment, dimensionless

$s_1$ maximum storage under dry antecedent conditions, mm

$W_1$ weighting factor, dimensionless

$W_2$ weighting factor, dimensionless

$$f_s = q / q_{sat} \qquad (12)$$

where

$q$ volume water fraction of surface soil

$q_{SAT}$ volume water fraction at saturation

$W_1$ and $W_2$ are weighting factors, calculated from the curve number for dry, $N_1$, average, $N_2$, and wet, $N_3$, antecedent conditions (Garen, 1996).

$$N_1 = \frac{N_2}{2.281 - 0.01281 N_2} \qquad (13)$$

$$N_3 = \frac{N_2}{0.427 + 0.00573 N_2} \qquad (14)$$

where

$N_n$ Curve number for antecedent condition n

and,

$$s_n = 250\left(\frac{100}{N_n} - 1\right) \qquad (15)$$

where

$s_n$ maximum storage under antecedent condition n, mm

then,

$$W_1 = \ln\left(\frac{1}{1 - s_3/s_2} - 1\right) + W_2 \qquad (16)$$

$$W_2 = 2\left[\ln\left(\frac{0.5}{1 - s_2/s_1} - 0.5\right) - \ln\left(\frac{1}{1 - s_2/s_1} - 1\right)\right] \qquad (17)$$

Surface runoff due to saturated soil, $R_2$, is calculated from;

$$R_2 = Pond + P - Pond' \qquad (18)$$

where

$R_2$ runoff due to saturated soil, mm
$P$ gross rainfall, mm
$Pond$ ponding depth, mm
$Pond'$ maximum allowable ponding depth, mm

Total surface runoff, $R$, is the sum of the two components.

$$R = R_1 + R_2 \qquad (19)$$

## 5. OUTPUTS

### 5.1 Open water evaporation

Open water evaporation occurs only if there is ponded water on the surface. The rate of open water evaporation is proportional to the reference evapotranspiration;

$$Eo_i = ETo_i / Kp \quad (20)$$

where
$Eo_i$ open water evaporation on day i, mm
$ETo_i$ reference evapotranspiration on day i, mm
$Kp$ open water evaporation (pan) coefficient, dimensionless, = 0.80

## 5.2 Soil evaporation

### *5.2.1 Potential soil evaporation*

The potential soil evaporation on any day is given by;

$$Eso_i = ETo_i \quad (21)$$

where
$Eso_i$ potential soil evaporation on day i, mm
$ETo_i$ reference evapotranspiration on day i, mm

### *5.2.2 Actual soil evaporation*

The evaporation from bare soil is calculated as a two stage process, following the method of Richie (1972).

Stage 1 starts on the first day after wetting[2] and lasts until a maximum cumulative evaporation, U. During stage 1, evaporation is limited by the atmosphere, therefore;

$$Es_i = Eso_i \quad (22)$$

where
$Es_i$ soil evaporation on day i, mm $d^{-1}$

During stage 2, evaporation is limited by the wetness of the soil, and the evaporation rate is determined from the time since wetting,

$$Es_i = a\ t_2^{1/2} - a\ (t_2-1)^{1/2} \quad (23)$$

where
$Es_i$ soil evaporation on day i, mm
$a$ constant, mm $d^{-1/2}$
$t_2$ time since the start of stage 2, d

Methods used to calculate $t_2$ following partial wetting and adjustment of soil evaporation on rain days are given in Richie (1972).

[2] Wetting = rain in excess of potential soil evaporation.

## 5.3 Crop transpiration

### *5.3.1 Potential crop transpiration*

The potential crop transpiration on any day is given by;

$$To_i = ETo_i * Kc_{max} \qquad (24)$$

where

$To_i$ potential transpiration on day i, mm

$Kc_{max}$ ratio of potential transpiration to reference evapotranspiration at maximum cover

### *5.3.2 Actual crop transpiration*

Actual plant transpiration per unit area of plant, is assumed to occur at the potential rate whilst the root zone soil water content is between field capacity (FC) and the easily available water capacity (EAWC). For excess water, it decreases linearly to zero when the root zone soil water content reaches saturation (SAT). For restricted water supply, it decreases linearly to permanent wilting point (PWP) and remains zero thereafter (Figure 3). This has been shown to be an acceptable simplification for irrigated conditions (Brisson, 1998).

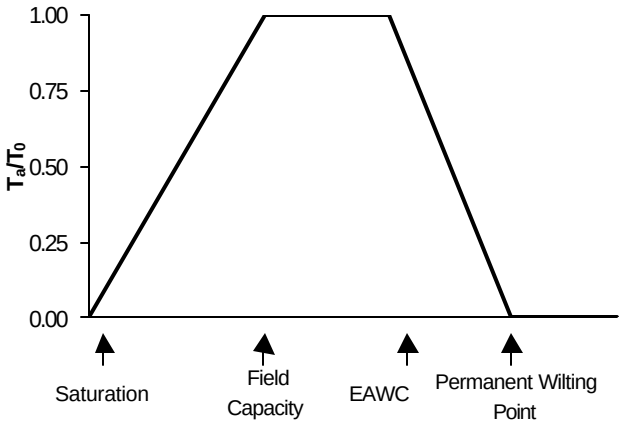



**Figure 3. Relative plant transpiration as a function of soil water content.**

Actual plant transpiration is then,

$$Ta_i = To_i \frac{Ta_i}{To_i} \qquad (25)$$

where

$Ta_i$ actual transpiration on day i, mm

$To_i$ potential transpiration on day i, mm

### *5.3.3 Adjustment for available precipitation*

When rain falls on dry soil, a proportion of the rainfall will be readily available to the crop, even if the soil profile is at an otherwise limiting deficit. Therefore, a pool of 'available precipitation' is maintained in the soil that will be depleted preferentially, at the potential rate.

As the start of each day any rainfall or irrigation on that day is added to the pool of available precipitation,

$$P'_i = P'_{i-1} + P_i + \mathrm{I}_i \qquad (26)$$

During that day, all rainfall and irrigation will therefore be available at the potential rate. However, at the end of the day, the pool of available precipitation will have been depleted by an amount equal to the actual evapotranspiration. Also a fraction of the day's rainfall and irrigation will have been redistributed through the soil profile and will be available at the limited rate. Thus, at the end of the day,

$$P'_i = P'_{i-1} + \frac{P_i + \mathrm{I}_i - ET_i}{2} \qquad (27)$$

where

$P'_i$ available precipitation on day i, mm
$P_i$ rainfall on day i, mm
$I_i$ irrigation on day i, mm
$ET_i$ actual evapotranspiration on day i, mm

The upper and lower limits of the pool of available precipitation are the easily available water capacity of the root zone and zero respectively.

Actual transpiration is adjusted for rain days and available precipitation by the following;

| *Condition* | *Ta* | |
|---|---|---|
| *(Ta + P') ³ To* | *To* | |
| *(Ta + P') < To* | *Ta + P'* | *(28)* |

where

Ta actual transpiration, mm
To potential transpiration, mm
P' available precipitation, mm

## 5.4 Effect of salinity on crop transpiration

The impact of soil salinity on transpiration is simulated using the method of Allen *et al*. (1998).

$$K_s = \left(1 - \frac{bs}{100Ky}(ECs - ECs')\right) \qquad (29)$$

where

*Ks* transpiration reduction factor for salinity, dimensionless

*Ky* yield response factor due to water stress, dimensionless

*bs* reduction in yield due to salinity, % (dS $m^{-1}$)$^{-1}$

*ECs* Average electrical conductivity of saturation extract for the root zone, dS $m^{-1}$

*ECs'* Threshold electrical conductivity of saturation extract, dS $m^{-1}$

Typical values of *ECe'*, *b* and *Ky* are given in Allen et al. (1998).

### *5.4.1 Partitioning of transpiration between compartments*

If the root depth is greater than the depth to the water table (i.e. part of the root zone is below the water table), all transpiration is assumed to take water from the capillary fringe, hence it is taken from the water table. Otherwise, plant transpiration is partitioned between the upper compartment (compartment 0) and the remainder of the root zone (compartment 1) in proportion to the depth of available water (i.e. in excess of permanent wilting point) in each compartment.

## 5.5 Evaporation from mulch

Evaporation is assumed to occur from the mulch cover only on days when it is wetted by rainfall or irrigation. Taking a maximum storage on the mulch surface of 2.0 mm, the following conditions are set;

| Condition | *Em* |
|---|---|
| *(P + I) = 0* | 0 |
| *(P + I) £ 2* | *P + I* or *ETo* whichever is the smaller |
| *(P + I) > 2* | 2.0 or $ET_o$ whichever is the smaller |

where

*Em* evaporation from mulch cover, mm $d^{-1}$

*ETo* reference evapotranspiration, mm $d^{-1}$

## 5.6 Actual evapotranspiration

If the soil is not ponded, the actual evapotranspiration from the soil is taken as the weighted average of actual crop transpiration, soil evaporation and evaporation of intercepted water from the mulch cover.

$$ETa = T_a \times C_i + E_s \times (1 - C_i - M_i) + E_m \times M_i \qquad (30)$$

where

$C_i$ crop cover fraction on day i, dimensionless

$M_i$ mulch cover fraction on day i, dimensionless

If the surface is ponded then

$$ETa = Eo_i \qquad (31)$$

## 5.7 Drain flow

### *5.7.1 Flow to drains*

The flow to the drains is a function of the mid-drain water table height (after Youngs *et al*., 1989).

$$q_d = 1000 \frac{K}{\left(L/2\right)^b} \left( \left( \frac{f}{2} \right)^b - h^b \right) \qquad (32)$$

where

$q_d$ flow to the drains, mm $d^{-1}$

K saturated hydraulic conductivity, m $d^{-1}$

L drain spacing, m

$\phi$ ditch water level or drain diameter, m

h mid-drain water table position, m above drain depth

$\beta$ exponent dependant on the depth to the impermeable layer, dimensionless

and,

$$b = 2 \left( \frac{d_0}{L/2} \right)^{\frac{d_0}{L/2}} \quad for \ \frac{d_0}{L/2} < 0.35 \qquad (33)$$

$b = 1.36$ otherwise

where,

$d_0$ depth from the drain to the impermeable layer, m

### *5.7.2 Capillary rise*

The maximum contribution of groundwater to transpiration, *Tgw*, and evaporation, *Egw*, are functions of the difference between the root depth (for transpiration) or soil surface (for evaporation) and the water table position and the hydraulic properties of the soil (Gardner, 1958).

If the water table is below half of the root depth, (z > r / 2) then

$$e = 1000\left(\frac{K}{\exp\left(c\left(z_w - \frac{r}{2}\right)\right) - 1}\right) \qquad (34)$$

where

| | |
|---|---|
| e | the potential contribution of groundwater to ET, mm $d^{-1}$ |
| K | saturated hydraulic conductivity, m $d^{-1}$ |
| c | empirical parameter, $m^{-1}$ |
| r | root depth, m |
| $z_w$ | depth to water table, m |

If the water table is above half the root depth, the soil is not limiting and, e = 1000 mm $d^{-1}$.

The parameter, *c*, is a soil texture / structure parameter that represents the relative importance of gravity and capillary forces during water movement in unsaturated soil. Where movement is dominated by gravity, *c* is large and where movement in dominated by capilarity, *c* is small (Reynolds and Elrick, 1991, Pullan, 1990). As *c* is difficult to estimate, it has been related to the hydraulic conductivity of the soil (Gilbert, Pers. Comm.);

$$c = 8.85K + 2.72 \qquad (35)$$

where

| | |
|---|---|
| c | empirical parameter, $m^{-1}$ |
| K | saturated hydraulic conductivity, m $d^{-1}$ |

The effect of depth to water table (z – r/2) and hydraulic conductivity is shown in Figure 4.

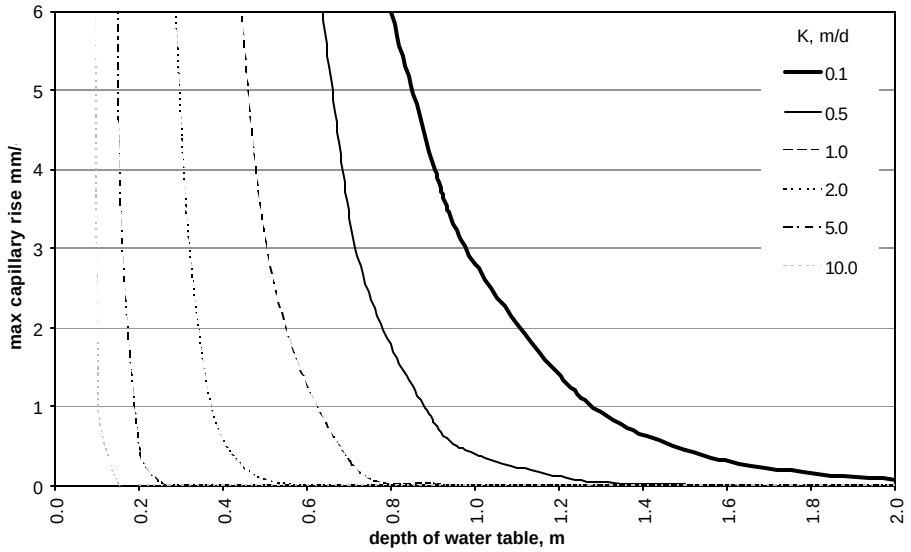



**Figure 4 Maximum capillary rise in relation to depth from water table to mid-root zone and hydraulic conductivity.**

The actual contribution from groundwater is the maximum of $ET_{max}$ and $ET_o$. If the water table is above half the drain depth, all the transpiration is taken from the water table.

### *5.7.3 Additions to the water table from seepage*

Seepage from irrigation canals, $q_s$, is assumed to supply a constant addition to the water table.

### *5.7.4 Losses from the water table due to tubewell drainage*

Tubewell drainage, $q_t$, is assumed to extract water from the water table at a constant rate.

### *5.7.5 The net flux from the water table*

The net flux from the water table is

$$V_s = E_{gw} + T_{gw} + q_t - q_u - q_s \qquad (36)$$

where

| | |
|---|---|
| *Vs* | net flux from the water table to the root zone, mm $d^{-1}$ |
| $E_{gw}$ | contribution from water table to soil evaporation, mm $d^{-1}$ |
| $T_{gw}$ | contribution from water table to transpiration, mm $d^{-1}$ |
| $q_t$ | daily extraction by tubewells, mm $d^{-1}$ |
| $q_u$ | drainage from the lower unsaturated compartment, mm $d^{-1}$ |
| $q_s$ | daily addition from seepage, mm $d^{-1}$ |

### *5.7.6 Calculation of water table position*

$$h_i = h_{i-1} - \frac{q_d + V_s}{1000m} \qquad (37)$$

where

| | |
|---|---|
| $h_i$ | height of the mid-drain water table position above drain depth on day i, m |
| $q_d$ | flow to drains, mm $d^{-1}$ |
| *Vs* | net flux from the water table to the root zone, mm $d^{-1}$ |
| *m* | drainable porosity, dimensionless |

and,

$$m = q_{SAT} - q \quad \textit{for a rising water table} \qquad (38)$$
$$m = q_{SAT} - q_{FC} \quad \textit{for a falling water table}$$

# 6. SOIL WATER RE-DISTRIBUTION

## 6.1 Drainage from compartment to compartment

If the volume water fraction of any compartment is brought above saturation any excess is assumed to be transferred to the compartment below immediately by drainage.

If the volume water fraction is between the field capacity and saturation then the drainage released from the compartment is calculated from (Raes and van Aelst, 1985);

$$q = t \ \ (q - q_{FC})\left(e^{(q - q_{FC})} - 1\right) / \left(e^{(q_{SAT} - q_{FC})} - 1\right) \times 1000 mm/m \qquad (39)$$

where

| | |
|---|---|
| $q$ | drainage from compartment, mm / m of compartment thickness / d |
| $\tau$ | drainage constant, dimensionless |
| $q$ | volume water fraction, dimensionless |
| $q_{FC}$ | volume water fraction at field capacity, dimensionless |
| $q_{SAT}$ | volume water fraction at saturation, dimensionless |

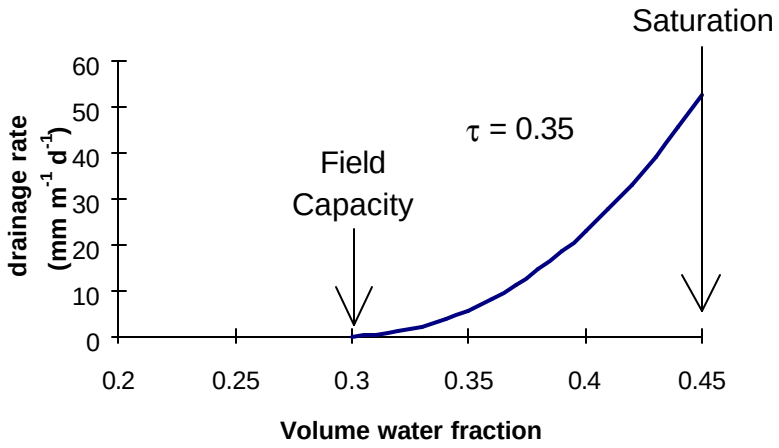



**Figure 5. Example of drainage rate function**

## 6.2 Soil water content

| Store | Gains | Losses |
|---|---|---|
| Compartment 0 | Effective rainfall & irrigation | Soil evaporation |
| | | Plant transpiration |
| | | Drainage |
| Compartment 1 | Drainage from compartment 0 | Plant transpiration |
| | | Drainage |
| Compartment 2 | Drainage from compartment | Drainage |

| | | |
|---|---|---|
| | 0 or 1 | |
| Compartment 3 | Drainage from compartment 1 or 2 | Capillary rise<br>Drain flow |

### *6.2.1 Compartment 0*

The soil water content of compartment 0 is calculated from the water content of the previous day, plus additions of effective rainfall and irrigation and minus losses of ET and drainage.

### *6.2.2 Compartment 1*

The soil water content of compartment 1 is calculated from the water content of the previous day, plus additions of drainage from the surface compartment and the extension of the root zone into compartment 2, less losses due to evapotranspiration and drainage to compartment 2.

$$W_{1,i} = W_{1,i-1} + q_{0,i} + (r_i - r_{i-1}) * 1000 * q_{2,i-1} - Ta_{1,i} - q_{1,i} \qquad (40)$$

where

$W_{j,i}$ water content of compartment j on day i, mm
$r_i$ root depth on day i, m
$\theta_{2,i}$ volume water fraction of compartment 2 on day i
$Ta_{j,i_i}$ actual transpiration from compartment *j* on day i, mm
$q_{j,i}$ drainage from compartment *j* on day i, mm

### *6.2.3 Compartment 2*

The soil water content of compartment 2 is calculated from the water content of the previous day, plus additions of drainage from above, less drainage out of compartment 2.

$$W_{2,i} = W_{2,i} + q_{1,i} - q_{2,i} \qquad (41)$$

where

$W_{j,i}$ water content of compartment *j* on day i, mm
$q_{j,i}$ drainage from compartment *j* on day i, mm

### *6.2.4 Volume water fraction*

The volume water fraction of either compartment is calculated from;

$$q = W / z \qquad (42)$$

where

$\theta$ volume water fraction of compartment, dimensionless

W water content of compartment, mm
z compartment thickness, mm

## 7. THE SALT BALANCE MODEL

The model is a salt mass balance of a one-dimensional profile with boundaries and compartments as for the water balance model (see page 1).

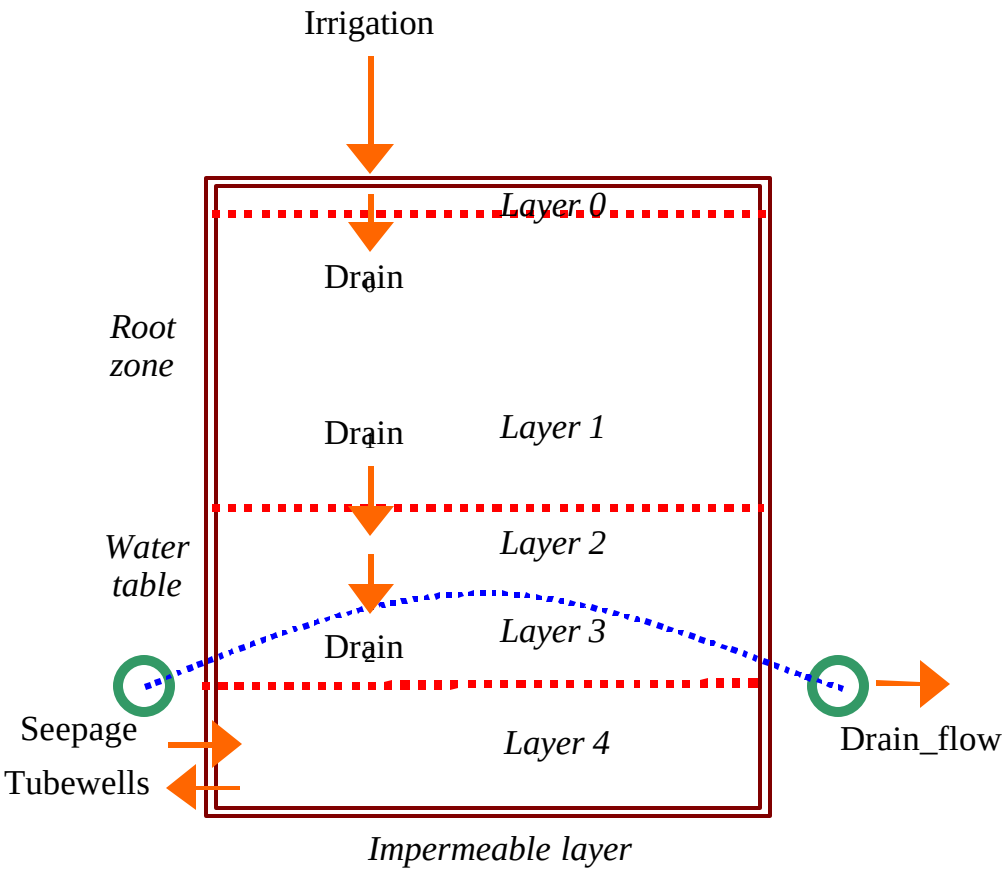



**Figure 6 Overview of the salt balance model.**

### 7.1 Inputs

The two inputs of salt to the systems are from irrigation water applied at the surface and seepage from canals. Seepage is assumed to contribute directly to the water table below drain depth. The daily input to the surface is calculated from;

$$S_I = I * EC_I \qquad (43)$$

Where
$S_I$ mass of salt added by irrigation water, mm dS $m^{-1}$ $d^{-1}$
$I$ depth of irrigation water applied, mm $d^{-1}$
$EC_I$ electrical conductivity of irrigation water, dS $m^{-1}$.

The input from seepage is,

$$Ss = Qs * EC_I \qquad (44)$$

where

*Ss* mass of salt added by seepage, mm dS $m^{-1}$ $d^{-1}$
*Qs* depth of seepage, mm $d^{-1}$
$EC_I$ electrical conductivity of irrigation water, dS $m^{-1}$.

## 7.2 Outputs

The outputs of salt are in the drainage water and water pumped from tubewells.

The quality of the drain water is a weighted average of the water quality above and below the drain depth. The daily output from the drains is calculated from;

$$S_d = Q * (f * EC_4 + (1 - f) * EC_3) \qquad (45)$$

Where

$S_d$ salt removed in drain water, mm dS $m^{-1}$ $d^{-1}$
*Q* drain flow, mm $d^{-1}$
*f* fraction of drain flow from below drain depth, dimensionless
$EC_j$ electrical conductivity of soil water in compartment j, dS $m^{-1}$

Assuming that the hydraulic conductivity above and below the drains is the same, then,

$$f = \frac{8hd}{8hd + 4h^2} \qquad (46)$$

where

*h* height of the mid-drain water table above the drain depth, m
*d* Hooghoudt's equivalent depth, m

and Hooghoudt's equivalent depth may be approximated from (Wesseling, 1979),

$$d = \frac{d_0}{1 + \left(\frac{8}{p}\frac{d_0}{L}\right)\ln\left(\frac{d_0}{\frac{1}{4}p f^2}\right)} \qquad (47)$$

where

$d_0$ depth from the drain to the impermeable compartment, m
*L* drain spacing, m
*f* drain diameter, m

Salt remove by tubewell drainage is,

$$S_T = Q_T * EC_4 \quad (48)$$

where

$S_T$ salt removed by tubewells, mm dS $m^{-1}$ $d^{-1}$

$Q_T$ rate of pumping from tubewells, mm $d^{-1}$,

## 7.3 Salt redistribution between compartments

The transfer of salt between soil compartments is driven by the transfer of water. A complete mixing model is assumed, such that;

$$S_{j,i} = S_{j,i-1} + Sd_{j-1,i} - Sd_{j,i} \quad (49)$$

where

$S_{j,i}$ mass of salt in compartment j on day i, mm dS $m^{-1}$ $d^{-1}$

$Sd_{j,i}$ mass of salt in the water leaving compartment j on day i, mm dS $m^{-1}$ $d^{-1}$

$$Sd_j = q_j * EC_j * Le \quad (50)$$

Where

$Sd_j$ mass of salt in the water leaving compartment $_j$, mm dS $m^{-1}$ $d^{-1}$

$q_j$ rate of drainage from compartment $_j$, mm $d^{-1}$

$EC_j$ electrical conductivity of soil water in compartment $_j$, dS $m^{-1}$

$Le$ leaching efficiency, dimensionless

## 7.4 Electrical conductivity of saturation extract

The electrical conductivity of the saturation extract, *ECs*, is often used as a measure of soil salinity. The *ECs* of the unsaturated compartments is calculated from;

$$ECs = EC\frac{q}{q_{paste}} \quad (51)$$

where

*ECs* electrical conductivity of saturation extract, dS/m

*EC* electrical conductivity, dS/m

$q$ volume water fraction, dimensionless

$q_{paste}$ volume water fraction of saturated paste, dimensionless

## 7.5 Target salinity

It is possible to increase irrigation to provide leaching to a target salinity. The irrigation requirement is calculated as follows;

Total salt in profile before irrigation (dS$m^{-1}$ mm),

$$S = \sum_{i=2}^{i=0} S_i \qquad (52)$$

where
$S_i$ = salt in compartment $i$, $dSm^{-1}$

Water content before irrigation (mm),

$$WC = \sum_{i=2}^{i=0} WC_i \qquad (53)$$

where
$WC_i$ = water in compartment $i$, mm

Drainage (mm),

$$D = WC + I - (z.q_{FC}) \qquad (54)$$

where
$z$ = depth to drains, mm
$q_{FC}$ = volume water fraction at field capacity, mm
$I$ = Irrigation application, mm

Salt removed in drainage water ($dSm^{-1}$ mm),

$$S_d = D\frac{(S + I.EC_w)}{(WC + I)}Le \qquad (55)$$

where
$Le$ = leaching efficiency, dimensionless
$EC_w$ = electrical conductivity of irrigation water, $dSm^{-1}$

Salt remaining after irrigation ($dSm^{-1}$ mm),

$$S' = S + I.EC_w - S_d \qquad (56)$$

Electrical conductivity of soil saturation extract after irrigation ($dSm^{-1}$),

$$EC'_e = \frac{S'}{z q_{paste}} \qquad (57)$$

where
$q_{paste}$ = volume water fraction of saturated soil paste

Combining the above, the electrical conductivity of soil saturation extract after irrigation ($dSm^{-1}$),

$$EC'_e = \frac{S + I.EC_w - D\dfrac{(S + I.EC_w)}{(WC + I)}le}{z.q_{paste}} \qquad (58)$$

The initial estimate of irrigation requirement is set at the soil water deficit = $z.q_{FC} - WC$, and the irrigation amount is increased until $EC'_e$ = target salinity.

## 8. GENERATION OF DEFAULT SOIL HYDRAULIC PARAMETERS

A range of soil hydraulic parameters are given in Rawls *et al.* (1982). Most of what follows is taken from that paper.

> $\theta_{sat}$ is the volume water fraction at saturation is taken to be the porosity given in Rawls *et al.* (1982).
>
> $\theta_{pwp}$ is the volume water fraction at permanent wilting point is taken to be the water retained at -15bar tension given in Rawls *et al.* (1982).

The field capacity volume water fraction and the drainage parameter, $\tau$, were determined by simulation. A saturated soil was simulated and allowed to drain freely under gravity over a 20 day period (with a zero flux boundary at the soil surface) using the model SWATRE (Belmans, *et al.* 1983). In SWATRE, the soil hydraulic properties are represented by the parameters of the van Genuchten method (van Genuchten, 1980).

- $\theta_{sat}$ was taken from above.
- $\theta_{res} \approx$ zero.
- Saturated hydraulic conductivity was taken from Rawls *et al.* (1982).
- $a = 1/y_{bub}$ *(59)*
- where $\psi_{bub}$ is the bubbling pressure given in Rawls *et al*. (1982).
- $n = l + 1$, *(60)*
- where $\lambda$ is the pore size distribution factor given in Rawls *et al*. (1982).
- $m = 1 - 1/n$ *(61)*
- (van Genuchten, 1980)
- $L = m \times 2.5$ *(62)*
- (van Genuchten, 1980)

The values of $\tau$ and $\theta_{fc}$ were determined by optimisation and minimising the sum of the squares of the difference between the soil water content predicted by SWATRE and that predicted by;

$q_i = q_{i-1} - dr_{i-1}$, and, *(63)*

$$dr = t\ \left(q_{i-1} - q_{FC}\right)\left(e^{(q - q_{FC})} - 1\right) / \left(e^{(q_{SAT} - q_{FC})} - 1\right) \times 1000mm / m \quad (64)$$

where

$dr_i$ drainage on day i, mm / m

$\tau$ drainage constant

$\theta_i$ volume water fraction on day $_I$

$\theta_{fc}$ volume water fraction at field capacity

$\theta_{sat}$ volume water fraction at saturation

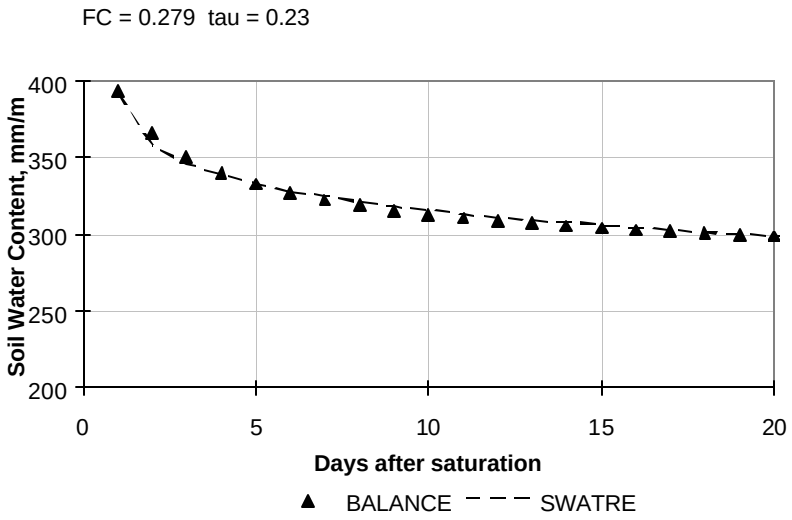



**Figure 7 Example of fitted drainage parameters for a loam soil**

**Table 2 Default soil physical parameters**

| Texture Class | $\theta_{sat}$ | $\theta_{fc}$ | $\theta_{pwp}$. | U mm | $\alpha$ | $\tau$ | N2 | $K_{sat}$ |
|---|---|---|---|---|---|---|---|---|
| Sand | 0.437 | 0.115 | 0.033 | 10 | 3.5 | 0.69 | 67 | 5.040 |
| Loamy Sand | 0.437 | 0.168 | 0.055 | 10 | 3.5 | 0.51 | 67 | 1.464 |
| Sandy Loam | 0.453 | 0.245 | 0.095 | 10 | 3.5 | 0.37 | 67 | 0.624 |
| Loam | 0.463 | 0.279 | 0.117 | 10 | 3.5 | 0.23 | 81 | 0.312 |
| Silt Loam | 0.501 | 0.324 | 0.133 | 10 | 3.5 | 0.17 | 81 | 0.163 |
| Sandy Clay Loam | 0.398 | 0.241 | 0.148 | 10 | 3.5 | 0.17 | 89 | 0.103 |
| Clay Loam | 0.464 | 0.321 | 0.197 | 10 | 3.5 | 0.11 | 89 | 0.055 |
| Silty Clay Loam | 0.471 | 0.350 | 0.208 | 10 | 3.5 | 0.09 | 89 | 0.036 |
| Sandy Clay | 0.430 | 0.311 | 0.239 | 10 | 3.5 | 0.09 | 89 | 0.029 |
| Silty Clay | 0.479 | 0.371 | 0.250 | 10 | 3.5 | 0.08 | 89 | 0.022 |
| Clay | 0.475 | 0.368 | 0.272 | 10 | 3.5 | 0.06 | 89 | 0.014 |

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