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WaSim
Technical Manual

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Authors; Tim Hess (Cranfield University)
Peter Leeds-Harrison (Cranfield University)
Chris Counsell (HR Wallingford)

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HR Wallingford
Howbery Park
Wallingford
Oxfordshire
OX10 8BA
UK

Institute of Water and Environment
Cranfield University
Silsoe
Bedford
MK45 4DT
UK

http://www.hrwallingford.co.uk/

http://www.silsoe.cranfield.ac.uk/

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Symbol	Description	Units
α	soil evaporation constant, mm d$^{-½}$	mm d$^{-½}$
τ	drainage coefficient	dimensionless
θ	volume water fraction	dimensionless
ϕ	ditch water level or drain diameter	m
μ	drainable porosity	dimensionless
Δr	daily root growth	m d^{-1}
θ_{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
θ_{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
β	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.

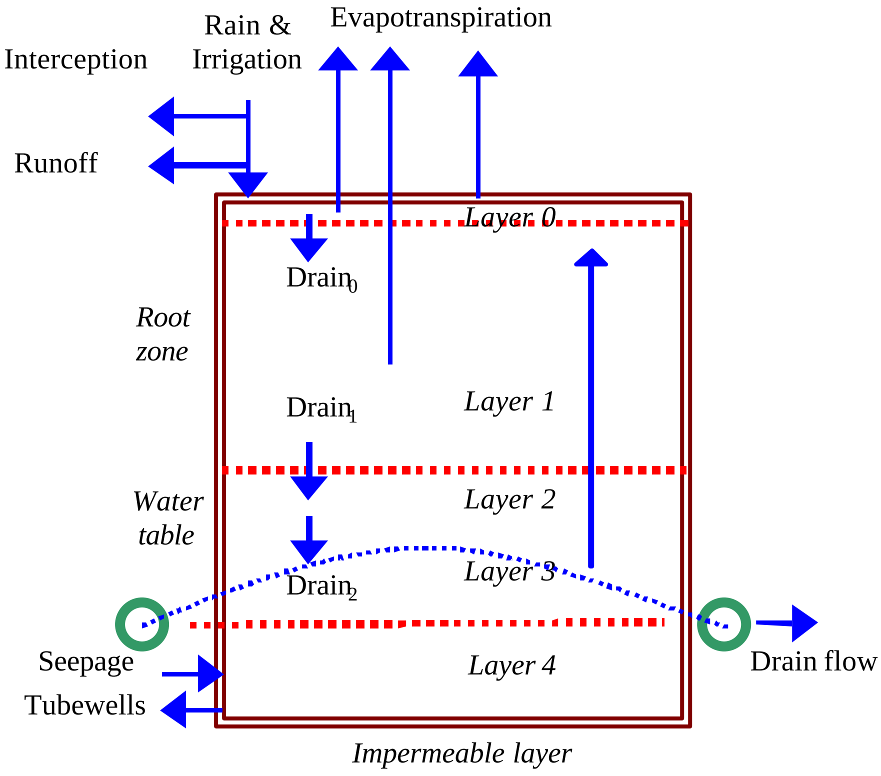

Figure 1. Overview of the soil water balance

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.

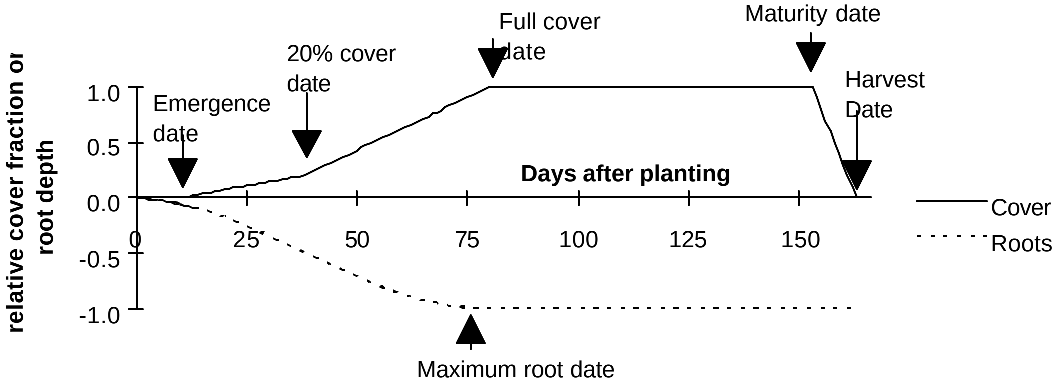

Figure 2. Crop cover and root depth development

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

Δr 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)

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

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;

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

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

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

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

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
θ_{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:

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

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

$$P_n = P\,(1\text{-}C) + (a + b\,P)\,C \qquad (P > a)$$

$$P_n = P \qquad (P \pounds a) \qquad (9)$$

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;

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

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;

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

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;

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

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,

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

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).

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[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).

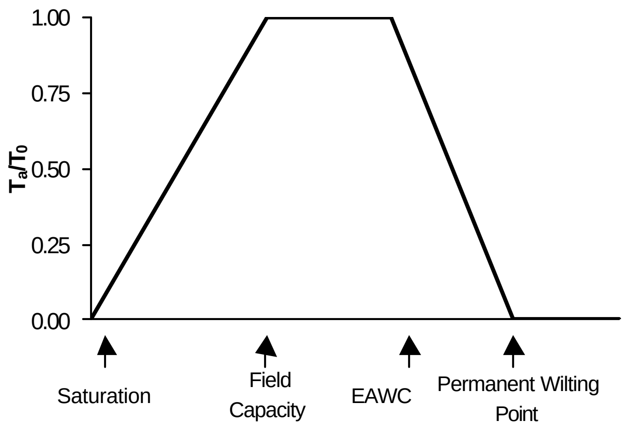

Figure 3. Relative plant transpiration as a function of soil water content.

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).

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

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.

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

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 <u>Drain flow</u>

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

ϕ ditch water level or drain diameter, m

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

β exponent dependant on the depth to the impermeable layer, dimensionless

and,

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

$$b = 1.36 \text{ otherwise}$$

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.

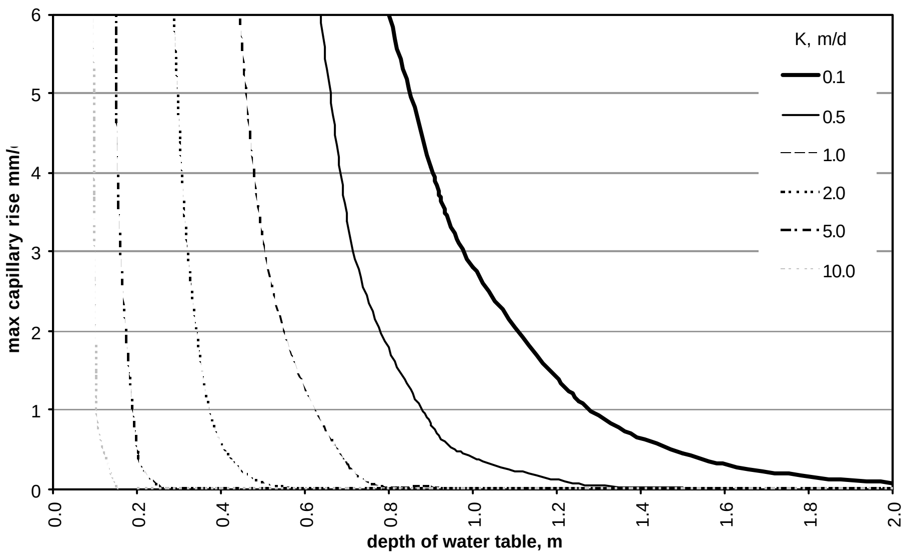

Figure 4 Maximum capillary rise in relation to depth from water table to mid-root zone and hydraulic conductivity.

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,

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

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
τ	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

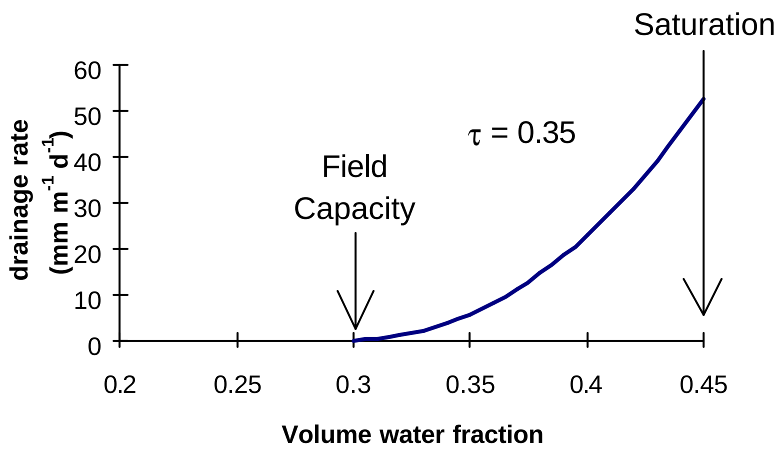

Figure 5. Example of drainage rate function

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 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

θ 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).

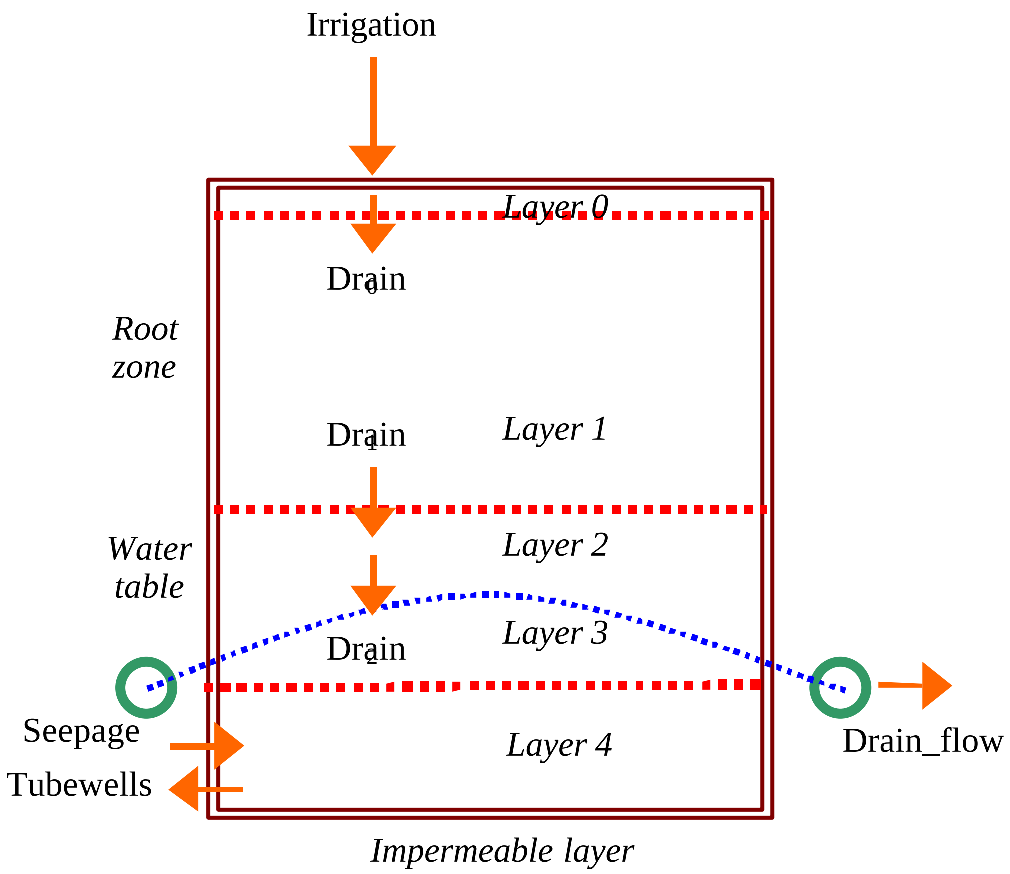

Figure 6 Overview of the salt balance model.

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,

$$S_T = Q_T * EC_4 \tag{48}$$

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;

$$S_{j,i} = S_{j,i-1} + Sd_{j-1,i} - Sd_{j,i} \tag{49}$$

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}

$$Sd_j = q_j * EC_j * Le \tag{50}$$

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;

$$ECs = EC \frac{q}{q_{paste}} \tag{51}$$

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 (dSm^{-1} mm),

$$S = \sum_{i=2}^{i=0} S_i \tag{52}$$

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

Water content before irrigation (mm),

$$WC = \sum_{i=2}^{i=0} WC_i \tag{53}$$

where
WC_i = water in compartment i, mm

Drainage (mm),

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

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),

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

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

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

$$S' = S + I.EC_w - S_d \tag{56}$$

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

$$EC'_e = \frac{S'}{z q_{paste}} \tag{57}$$

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.

> θ_{sat} is the volume water fraction at saturation is taken to be the porosity given in Rawls *et al.* (1982).
>
> θ_{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, τ, 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).

- θ_{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 ψ_{bub} is the bubbling pressure given in Rawls *et al.* (1982).
- n = $l + 1$, *(60)*
- where λ 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 τ and θ_{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;

$$q_i = q_{i-1} - dr_{i-1}, \text{ and,} \qquad (63)$$

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

where

dr_i	drainage on day i, mm / m
τ	drainage constant
θ_i	volume water fraction on day $_I$
θ_{fc}	volume water fraction at field capacity
θ_{sat}	volume water fraction at saturation

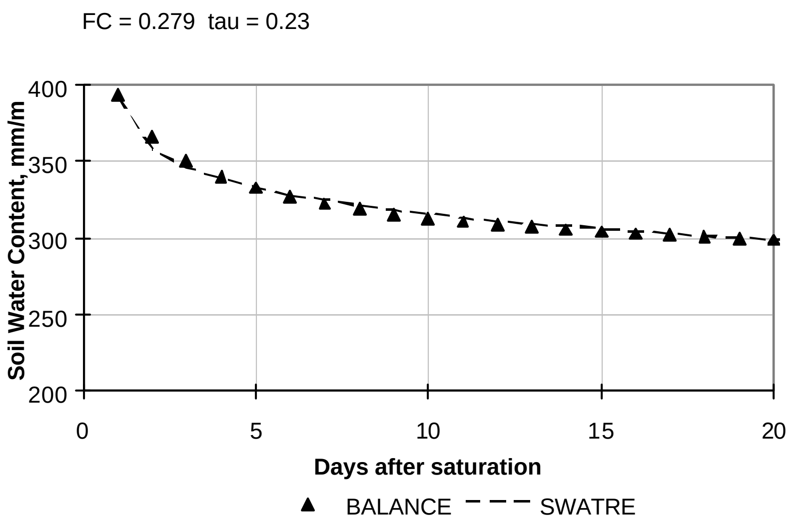

Figure 7 Example of fitted drainage parameters for a loam soil

Table 2 Default soil physical parameters

Texture Class	θ_{sat}	θ_{fc}	θ_{pwp}.	U mm	α	τ	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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