26 Water and Solute Mass Balance Models

This chapter describes the *WINDS* tipping bucket approach to water, salt, and nitrate transport in soils. The tipping bucket model is based on the law of conservation of mass (Fig. 26.1). The model runs quickly because rapid changes due to irrigation or storm events are simulated with conservation of mass, which allows for daily time steps. The algorithms march forward in time with Euler's finite difference method. Because the model is fast, it can simulate daily changes in water, salinity, and nitrogen at hundreds of locations within fields over a growing season.

The continuity equation can be written for any control volume (Fig. 26.1):

$$\Delta m_{cv} = m_{in} + m_{IR} - m_{out} \tag{26.1}$$

where

m_{in} = mass entering system, kg,
m_{out} = mass leaving system, kg,
m_{IR} = mass generated or lost within system by internal reaction, kg,
Δm_{cv} = change of mass within control volume, kg.

Water Mass Balance

The conservation of mass equation is written in terms of volume of water rather than mass because the density of water is constant in the range of soil temperature.

$$\Delta V_{cv} = V_{in} + V_{IR} - V_{out} \tag{26.2}$$

where

V_{in} = volume entering system, m^3,
V_{out} = volume leaving system, m^3,
V_{IR} = volume generated within system by internal reaction, m^3,
ΔV_{cv} = change of volume within control volume, m^3.

Equation 26.2 is used to calculate daily water volume change in the root zone. The change in volume is the difference between daily water inflow, outflow, and internal change.

The sources and sinks for the entire soil profile are shown in Fig. 26.2. The soil can be divided into layers with a volume balance written for each layer. In the tipping bucket model, it is assumed that water only flows downward through the root zone and freely drains below the soil profile. This assumption is appropriate for soils in which water redistribution takes place within a few days. Subsequent chapters describe upward and downward flow of water in the soil due to energy gradients. The tipping bucked model is used for irrigation or large storm events. Each soil layer is a control volume that is treated like a "bucket" from which water spills into the next layer when the "bucket" is full.

The soil is divided in layers in Fig. 26.3. Each of the layers is treated as a bucket that can hold a certain volume of water (Fig. 26.3). The volume of each bucket is the product of layer volume and field capacity. When the volume of the bucket is exceeded during an irrigation event, then excess water drains to the next layer. The internal reaction term is evapotranspiration.

Evapotranspiration can be treated like an internal reaction term ($V_{ET} = V_{IR}$) for soil water.

$$V_{in} - V_{out} - V_{ET} = \Delta V_{cv} \tag{26.3}$$

where

V_{ET} = volume lost to evapotranspiration during time step.

Layer water volume is the product of depth of water in the layer (equivalent to ponded depth but distributed within pores) and layer horizontal area, $\Delta x\ \Delta y$.

$$d_{in}\Delta x\ \Delta y - d_{out}\Delta x\ \Delta y - d_{ET}\Delta x\ \Delta y = \Delta d_{cv}\Delta x\ \Delta y \tag{26.4}$$

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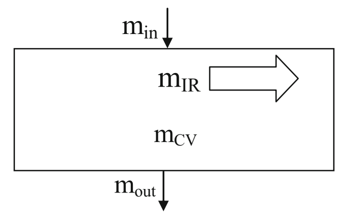


Fig. 26.1 Control volume for conservation of mass

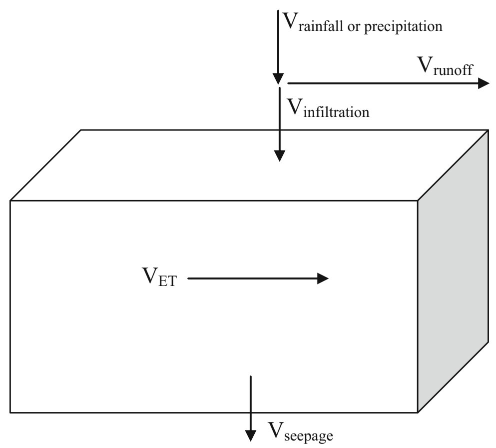


Fig. 26.2 Sources and sinks for water in a single layer

Divide Eq. 26.4 by Δx Δy

$$d_{in} - d_{out} - d_{ET} = \Delta d_{cv} \tag{26.5}$$

where

d_{in} = depth of water that flows into the layer, m,
d_{out} = depth of water that flows out of the layer, m,
d_{ET} = depth of water lost to evapotranspiration, m,
Δd_{cv} = change in depth of water within the layer, m,

The d_{in} term at the upper boundary (soil surface) is infiltration from storms or irrigation events. Infiltration is either specified in the *WINDS* program in the *Irr* worksheets, is calculated with the Green-Ampt model (Chap. 29), or is calculated with the NRCS curve number method. If a runoff flume is used at a site, then infiltration can be calculated based on precipitation, field area, and runoff volume.

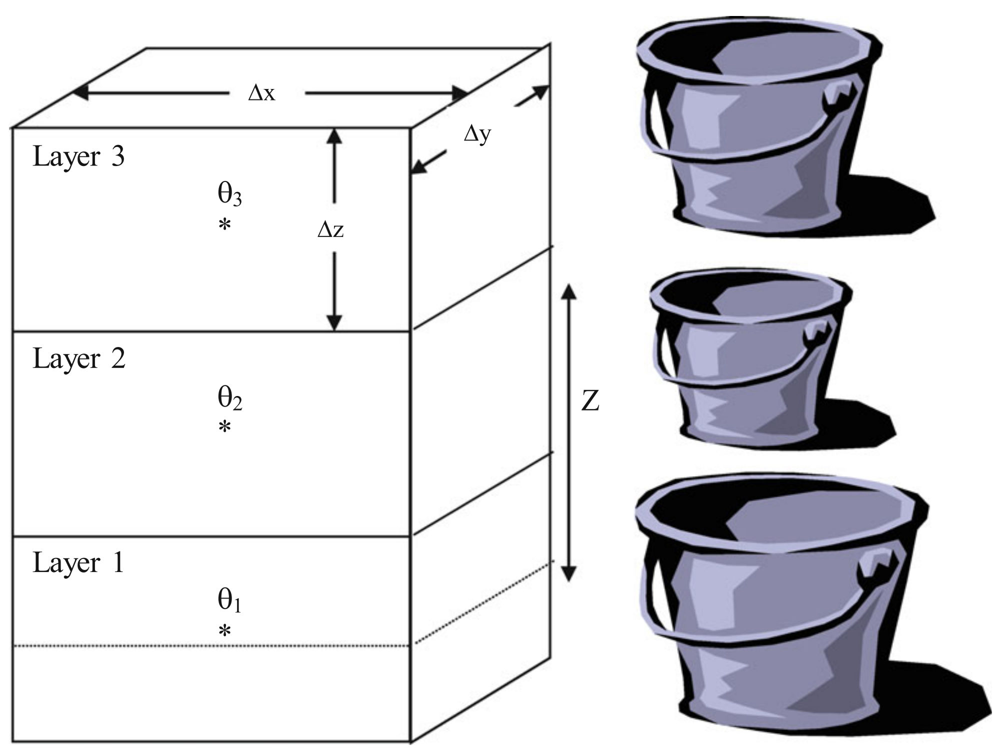
$$d_{RO} = V_{RO}/A_{field} \tag{26.6}$$

$$i = P - d_{RO} \tag{26.7}$$

where

i = infiltrated depth, m,
V_{RO} = volume of runoff from a field, m^3.
A_{field} = field area, m^2,
d_{RO} = depth of runoff, m.
P = precipitation depth, m.

Fig. 26.3 Layers in the soil profile for tipping bucket model



The water exiting across the lower boundary of the layer is seepage. Substitute water balance parameters into Eq. 26.5 to calculate change in the depth of water in the layer.

$$\Delta d_{cv} = i - d_{seepage} - d_{ET} \quad (26.8)$$

where

$d_{seepage}$ = depth leached below the layer, m,

The maximum depth of water that a layer can hold is the product of field capacity and layer depth.

$$d_{cv-max} = \theta_{fc}\Delta z \quad (26.9)$$

where

d_{cv-max} = Maximum depth of water in each layer, m,
θ_{fc} = Water content at field capacity, dimensionless.

The tipping bucket approach is sequential, beginning in the upper layer. If there is excess water in a layer after an infiltration event (exceeding field capacity), then the water is routed to the next layer. Then, the process repeats until there is no more seepage or the lower boundary is reached.

If there is seepage, then the final water content in the layer is field capacity. The calculation of seepage and final water content is calculated in three steps for each layer.

Step 1: Calculate initial depth of water in layer.

$$d_{initial} = \theta_{initial}\Delta z \quad (26.10)$$

where

$d_{initial}$ = initial depth of water in layer, m.
$\theta_{initial}$ = initial water content, ml/ml.
Step 2: Calculate sum of initial depth, infiltration, and ET.

$$d_{sum} = d_{initial} + i - d_{ET} \quad (26.11)$$

where

d_{sum} = antecedent water content + infiltrated depth, m.
Step 3: Calculate final water content and seepage

$$d_{sum} \geq d_{cv-max} \rightarrow \theta_{final} = \theta_{fc} \quad d_{seepage} = d_{sum} - d_{cv-max} \quad (26.12)$$

$$d_{sum} < d_{cv-max} \rightarrow \theta_{final} = d_{sum}/\Delta z \quad d_{seepage} = 0 \quad (26.13)$$

where

θ_{final} = final water content, m.

Example 26.1 During a two-day period, there are two storms. The first high intensity, storm has 3 cm precipitation depth. Runoff during and after the first storm is measured in a flume at the lower end of the 38 ha field: 3,800 m^3. A second low intensity storm adds 4 cm water to the soil profile, and there is no runoff. Model the soil as one layer that is 1.2 m deep. Average water content in the soil profile before the storm is 17 %. Field capacity is 20 %. The water table is well below the soil profile. Assume that evapotranspiration between the storms is negligible. Perform the water balance for each storm.

Calculate the maximum depth of water that the soil profile can hold

$$d_{cv-max} = \theta_{fc}\Delta z = 0.2(1.2m) = 0.24m$$

Find the depth of runoff during the first storm

$$d_{RO} = V_{RO}/A_{field} = 3{,}800m^3/\left(38ha\left(10{,}000m^2/ha\right)\right) = 0.01m$$

Find the depth of infiltration during the first storm

$$i = P - d_{RO} = 3cm - 1cm = 2cm = 0.02m.$$

Step 1: Calculate the initial depth of water in the soil profile.

$$d_{initial} = \theta_{initial}\Delta z = 0.17(1.2m) = 0.204m$$

Step 2: Calculate sum of initial depth and infiltration.

$$d_{sum} = d_{initial} + i = 0.204\,m + 0.02\,m = 0.224\,m$$

Step 3: Calculate final water content and seepage.

$$d_{sum} < d_{cv-max} \rightarrow \theta_{final} = d_{sum}/\Delta z = 0.224/1.2m = 0.187ml/ml \quad d_{seepage} = 0$$

Repeat calculation for second storm with $i = 0.04$.

Step 1: Calculate initial depth of water in soil profile.

$$d_{initial} = d_{initial} = \theta_{initial}\Delta z = 0.187(1.2m) = 0.224m$$

Step 2: Calculate sum of initial depth and infiltration.

$$d_{sum} = d_{initial} + i = 0.224m + 0.04m = 0.264m$$

Step 3: Calculate final water content and seepage.

$$d_{sum} \geq d_{cv-max} \rightarrow \theta_{final} = \theta_{fc} = 0.2ml/ml$$
$$d_{seepage} = d_{sum} - d_{cv-max} = 0.264 - 0.24 = 0.024m$$

If the soil is divided into layers (Fig. 26.3), then the three steps can be repeated for each layer. The *WINDS* model numbers layers from the bottom of the soil profile to the top. Thus, with two layers, the upper layer is layer number 2, and the mass balance is calculated as follows, where $d_{seepage\text{-}2}$ is the water that passes from layer 2 to layer 1.

$$\Delta d_{cv-2} = i - d_{seepage\ 2} - d_{ET-2} \tag{26.14}$$

The volume balance is written as follows for layers below the upper layer with seepage from the layer above entering the layer.

$$\Delta d_{cv-j} = d_{seepage\ j+1} - d_{seepage\ j} - d_{ET-j} \tag{26.15}$$

where

j = layer number.

Evapotranspiration is the product of total ET and fraction ET from each layer.

$$d_{ET-j} = ET_{frac-1} d_{ET} \tag{26.16}$$

$$\Delta d_{cv-j} = d_{seepage\ j+1} - d_{seepage\ j} - ET_{frac-j} d_{ET} \tag{26.17}$$

where

$ET_{frac\text{-}j}$ = fraction of ET that evaporates from layer j.

Example 26.2 Redo Example 26.1 with 3 layers that are 0.4 m deep. Initial water content in all layers is 0.17 and field capacity is 0.20.

The maximum water depth held by each layer is

$$d_{cv-max} = \theta_{fc} \Delta z = 0.20(0.4\text{m}) = 0.08\text{m}$$

Storm 1. Layer 3 (Upper layer)

Step 1. Calculate initial water depth.

$$d_{initial-3} = \theta_{initial-3} \Delta z = 0.17(0.4\text{m}) = 0.068\text{m}$$

Step 2. Calculate sum of initial depth and infiltration.

$$d_{sum-3} = d_{initial-3} + i = 0.068\text{m} + 0.02\text{m} = 0.088\text{m}$$

Step 3. Calculate final water content and seepage.

$$d_{sum-3} \geq d_{cv-max} \rightarrow \theta_{final-3} = \theta_{fc} = 0.2\text{ml/ml}$$
$$d_{seepage-3} = d_{sum-3} - d_{cv-max} = 0.088 - 0.08 = 0.008\text{m}$$

Storm 1. Layer 2

Step 2: Calculate sum of initial depth and infiltration.

$$d_{sum-2} = d_{initial-2} + d_{seepage-3} = 0.068\text{m} + 0.008\text{m} = 0.076\text{m}$$

Step 3: Calculate final water content and seepage.

$$d_{sum-2} < d_{cv-max} \rightarrow \theta_{final-2} = d_{sum-2}/\Delta z = 0.076\text{m}/0.4 = 0.19\text{ml/ml}\ d_{seepage-2} = 0$$

There is no seepage to the third layer and no change in water content. After the first storm, the depth of water in the first layer is 0.080 m and the depth of water in the second layer is 0.076 m. No water infiltrates to the third layer.

Storm 2. Layer 3

The second storm infiltration is 4 cm (0.04 m). The first layer is already at field capacity so the entire 0.04 m drains from layer 3 to layer 2.

Storm 2. Layer 2.

Step 1. Calculate initial water depth.

$$d_{initial-2} = \theta_{initial-2} \Delta z = 0.19(0.4\text{m}) = 0.076\text{m}$$

Step 2. Calculate sum of initial depth and infiltration.

$$d_{sum-2} = d_{initial-2} + d_{seepage-3} = 0.076\text{m} + 0.04\text{m} = 0.116\text{m}$$

Step 3. Calculate final water content and seepage.

$$d_{sum-2} \geq d_{cv-max} \rightarrow \theta_{final-2} = \theta_{fc} = 0.2\text{ml/ml}$$
$$d_{seepage-2} = d_{sum-2} - d_{cv-max} = 0.116 - 0.08 = 0.036\text{m}$$

Storm 2. Layer 1

Step 1. Calculate initial water depth.

$$d_{initial-1} = \theta_{initial-1} \Delta z = 0.17(0.4\text{m}) = 0.068\text{m}$$

Step 2. Calculate sum of initial depth and infiltration.

$$d_{sum\text{-}1} = d_{initial\text{-}1} + d_{seepage\text{-}2} = 0.068\text{ m} + 0.036\text{ m} = 0.104\text{ m}$$

Step 3. Calculate final water content and seepage.

$$d_{sum-1} \geq d_{cv-max} \rightarrow \theta_{final-1} = \theta_{fc} = 0.2\text{ml/ml}$$
$$d_{seepage-1} = d_{sum-1} - d_{cv-max} = 0.104 - 0.08 = 0.024\text{m}$$

Example 26.3 A crop with a 1 m root zone is planted in a soil with two layers.

$$\text{Layer1 (Upperlayer)}: \theta_{FC} = 0.20, \quad \theta_{PWP} = 0.10, \quad \text{layer depth } \Delta z = 0.6\text{m}, \quad ET_{frac} = 0.6$$
$$\text{Layer2 (Lowerlayer)}: \theta_{FC} = 0.26, \quad \theta_{PWP} = 0.11, \quad \text{layer depth } \Delta z = 0.4\text{m}, \quad ET_{frac} = 0.4$$

Total ET (d_{ET}) is 0.01 m/day. Four days after a storm filled the soil to field capacity, a second storm adds 3 cm to the soil. Calculate water contents and percent depletions before and after the second storm

Calculate water status before second storm based on ET between storms and initial θ_{fc}.

Layer 2 (Upper layer) $d_{cv\text{-}max} = 0.2(0.6) = 0.12$ m (four day time step)

Step 1. Calculate initial water depth.

$$d_{initial-2} = \theta_{initial-2}\Delta z = 0.2(0.6) = 0.12\text{m}$$

Step 2. Calculate sum of initial depth, infiltration, and ET.

$$d_{sum-2} = d_{initial-2} + i - ET_{frac-2}d_{ET} = 0.12\text{m} + 0\text{m} - (0.01\text{m/day})(0.6)(4\text{days}) = 0.096\text{m}$$

Step 3: Calculate final water content and seepage.

$$d_{sum-2} < d_{cv-max} \rightarrow \theta_{final-2} = d_{sum-2}/\Delta z = 0.096\text{m}/0.6\text{m} = 0.16\text{ml/ml} \quad d_{seepage-2} = 0$$

$$\text{Depletion} = (0.01\text{m/day})(0.6\text{m})(4\text{days}) = 0.024\text{m}$$
$$\text{TAW} = (\theta_{fc} - \theta_{pwp})\Delta z = (0.2 - 0.1)0.6\text{m} = 0.06\text{m}$$
$$\%\text{depletion} = D_r/\text{TAW}(100\%) = 0.024\text{m}/0.06\text{m}(100\%) = 40\%$$

Layer 1 (Lower layer) $d_{cv\text{-}max} = 0.26\ (0.4) = 0.104$ m

Step 1. Calculate initial water depth.

$$d_{initial-1} = \theta_{initial-2}\Delta z = 0.26(0.4\text{m}) = 0.104\text{m}$$

Step 2. Calculate sum of initial depth, infiltration, and ET.

$$d_{sum-1} = d_{initial-1} + d_{seepage-2} - ET_{frac-1}d_{ET} = 0.104\text{m} + 0 - (0.01\text{m/day})(0.4)(4\text{days}) = 0.088\text{m}$$

Step 3: Calculate final water content and seepage.

$$d_{sum-1} < d_{cv-max} \rightarrow \theta_{final-1} = d_{sum-1}/\Delta z = 0.088\text{m}/0.4\text{m} = 0.22\text{ml/ml}$$
$$d_{seepage-2} = 0$$

$$\text{Depletion} = (0.01\text{cm/day})(0.4\text{m})(4\text{days}) = 0.016\text{m}$$
$$\text{TAW} = (\theta_{fc} - \theta_{pwp})\Delta z = (0.26 - 0.11)0.4\text{m} = 0.06\text{m}$$
$$\%\text{depletion} = D_r/\text{TAW}(100\%) = 0.016\text{m}/0.06\text{m}(100\%) = 26\%$$

Calculate water status after second storm based on infiltration.

Layer 2 (Note that the time step is just the time of the storm)

Step 1. Calculate initial water depth.

$$d_{initial-2} = \theta_{initial-2}\Delta z = 0.16(0.6\text{m}) = 0.096\text{m}$$

Step 2. Calculate sum of initial depth, infiltration, and ET.

$$d_{sum-2} = d_{initial-2} + i - d_{ET-2} = 0.096\text{m} + 0.03\text{m} - 0\text{m} = 0.126\text{m}$$

Step 3: Calculate final water content and seepage.

$$d_{sum-2} \geq d_{cv-max} \rightarrow \theta_{final-2} = \theta_{fc} = 0.2\text{ml/ml}$$
$$d_{seepage-2} = d_{sum-2} - d_{cv-max} = 0.126 - 0.12 = 0.006\text{m}$$

$$\text{Depletion} = 0\text{m}$$
$$\%\text{depletion} = 0\%$$

Layer 1

Step 1. Calculate initial water depth.

$$d_{initial-1} = \theta_{initial-1}\Delta z = 0.22(0.4\text{m}) = 0.088\text{m}$$

Step 2. Calculate sum of initial depth, infiltration, and ET.

$$d_{sum-1} = d_{initial-1} + d_{seepage-2} - d_{ET-1} = 0.088\text{m} + 0.006\text{m} - 0\text{m} = 0.094\text{m}$$

Step 3: Calculate final water content and seepage.

$$d_{sum-1} < d_{cv-max} \rightarrow \theta_{final-1} = \theta_{sum-1}/\Delta z = 0.094m/0.4m = 0.235ml/ml$$
$$d_{seepage-2} = 0$$

$$\text{Depletion} = 0.104m - 0.094m = 0.01m$$
$$\%\text{depletion} = D_r/TAW(100\%) = 0.01m/0.06m(100\%) = 17\%$$

Salinity Mass Balance Model

Although there are many salinity sources and sinks that could be incorporated into the salinity mass balance model, it was shown in Chap. 4, that the sources and sinks can be ignored in a typical model of salinity in agricultural soils. All of the cations and anions can be lumped into one concentration term representing all forms of salinity, EC or C. The approach in the *WINDS* model is to calculate maximum solubility of the irrigation water and if salinity exceeds the maximum solubility, then salts are removed from the water phase. However, this level of salinity is not normally encountered in agricultural fields. The maximum solubility is a function of temperature, activity coefficients of ions in solution and numerous other parameters. Programs such as HYDRUS, available through the USDA-ARS Salinity Laboratory, consider salinity transformations in soil.

The mass of salt within a layer (m_{salt}) is the product of volume of the layer (V_{layer}), fraction of soil that is occupied by water (θ), and the concentration of salt within the soil-water (C).

$$m_{salt} = V_{layer} C\, \theta \tag{26.18}$$

where

C = salt concentration, mg salt /L water,
θ = initial water content in the layer, L water /L soil,
V_{layer} = volume of the layer, L.
m_{salt} = mass of salt within the layer, $mg/L_{soil}\ m^3$.

The change of salt mass within the control volume during a time step is

$$\Delta m_{salt} = \Delta(C\ V_{cv}\ \theta) = C_{final} V_{layer} \theta_{final} - C_{initial} V_{layer} \theta_{initial} \tag{26.19}$$

where

Δm_{salt} = change in mass of salt, $mg/L_{soil}\ m^3$.
$C_{initial}$ = initial salt concentration, mg salt /L water,
C_{final} = final salt concentration, mg salt /L water,
$\theta_{initial}$ = initial water content in control volume, L water/L soil,
θ_{final} = final water content in control volume, L water / L soil.

The salt influx is the product of water influx (V_{in}) and average salt concentration. Assuming piston flow through the layer and no water passing completely through the layer, the salt drained is the product of outflow (V_{out}) and average salt concentration in the layer's water.

$$m_{in} = V_{in} C_{in} \quad (L)(mg/L) = mg/L_{water} m^3 \tag{26.20}$$

$$m_{out} = V_{out} C_{initial} \quad (L)(mg/L) = mg/L_{water} m^3 \tag{26.21}$$

where

C_{in} = salt concentration in water entering the layer, mg salt / L water
$C_{initial}$ = Initial salt concentration in layer, mg salt /L water
V_{in} = Volume of water entering the layer, m^3,
V_{out} = Volume of water exiting the layer, m^3.

Plant uptake of salinity is neglected, and the change in mass of salt is simply the difference between influx and outflow.

$$\Delta m_{layer} = m_{in} - m_{out} \tag{26.22}$$

Substitute Eq. 26.32 into Eq. 26.29

$$C_{final} V_{layer} \theta_{final} - C_{initial} V_{layer} \theta_{initial} = V_{in} C_{in} - V_{out} C_{initial} \tag{26.23}$$

With a finite difference soil solute model of a layered soil, it is convenient to express the total mass of salt based on concentration and depth, mg/L_{soil} m, or mg/L_{water} m. Salt concentration is expressed as mg/L_{water}.

$$C_{final} \Delta z\ \theta_{final} - C_{initial} \Delta z\ \theta_{initial} = d_{in} C_{in} - d_{out} C_{initial} \tag{26.24}$$

Equation 26.24 can be rearranged to solve for final salt content.

$$C_{final} = \frac{d_{in}C_{in} - d_{out}C_{intial} + C_{intial}\ \Delta z\ \theta_{intial}}{\Delta z\ \theta_{final}} \quad (26.25)$$

Equation 26.25 is used in the *WINDS* model to calculate the concentrations in soil layers. Dimensional analysis shows that the units in Eqs. 26.24 and 26.25, mg/L_{soil} m_{soil}, or mg/L_{water} m_{water} (C d_{in}) can be converted to kg/ha by multiplying by 10:

$$C\Delta z\theta = \left(\frac{mg}{L_{water}}\right)\left(\frac{m}{1}\right)\left(\frac{L_{water}}{L_{soil}}\right) = \left(\frac{mg\ m}{L_{soil}}\right)$$

$$\text{kg/ha} = \left(\frac{mg}{L_{soil}}\right)\left(\frac{1\ kg}{10^6\ mg}\right)\left(\frac{10^3\ L}{m^3}\right)\left(\frac{10^4\ m^2}{ha}\right)$$

$$(soil\ depth\ (m)) = 10\left(\frac{mg}{L_{soil}}\right)(soil\ depth)$$

Concentration, C, in Eq. 26.35 can be replaced by EC.

$$EC_{final} = \frac{d_{in}\ EC_{in} - d_{out}\ EC_{initial} + EC_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}} \quad (26.26)$$

The units for the mass of salts in the layers is now (dS/m m), which is equal to mg/L m/640. Equation 26.26 can be applied to individual soil layers. With the tipping bucket model, the sequence of calculation for each time step is to first calculate the water movement beginning with the upper layer. Second, the salinity concentrations are calculated with Eq. 26.26 beginning with the upper layer and then moving downward through the soil profile from one layer to the next. The input to each layer is the seepage from the layer above. For the upper layer, Eq. 26.26 is written as

$$EC_{final} = \frac{i\ EC_{iw} - d_{seepage}\ EC_{initial} + EC_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}} \quad (26.27)$$

For layers (j) below the upper layer, Eq. 26.26 is written as

$$EC_{final} = \frac{d_{seepage\text{-}j+1}\ EC_{j+1} - d_{seepage\text{-}j}\ EC_{initial} + EC_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}} \quad (26.28)$$

If infiltration from above exceeds the available water storage capacity in the layer, (field capacity – water content) (layer depth), then Eq. 26.28 is invalid. In this case, the existing water and infiltrating water from above is mixed; the weighted average is (i EC_{iw} + $EC_{initial}$ $\theta_{initial}$ Δz)/(i + $\theta_{initial}$ Δz + Rain – ET). This average concentration is then the final layer concentration and the concentration of the seepage water below the layer.

Example 26.4 Using the parameters from Example 4.6, perform a transient analysis of salinity in 4 layers that are 0.5 m depth with a root zone depth that is 2.0 m deep. An irrigation is applied on the third day and every 7 days thereafter. Make hand calculations for the first 3 days for the upper two layers and verify that they agree with the *WINDS* model. Run the *WINDS* model simulation for 100 days beginning with DOY 1. Initial salinity of the saturated extract, EC_e, is 1.034 dS/m in all layers. Irrigation water salinity is 1.0 dS/m. $\theta_{FC} = 0.2$, $\theta_{PWP} = 0.1$, and $\theta_{sat} = 0.387$. MAD = 0.35. ET is 10 mm/day during the entire 100 days, and 40-, 30-, 20-, and 10-% of ET is extracted from the upper, next, next, and lower layers, respectively. Initial water content in all layers is field capacity, 0.2. First, calculate for no leaching, and then calculate for 15 % LF. The comparison is complicated by the fact that the *WINDS* model has an evaporation layer. This can be ignored by reducing the evaporation layer thickness to 1 cm, eliminating evaporation and transpiration from the evaporation layer, and setting the EC in the evaporation layer to the same concentration as the concentration in the irrigation water. Because the evaporation layer is 1 cm thick, the upper layer (below the evaporation layer) thickness in the *WINDS* model is 49 cm. In the following calculations, the calculations are more straightforward by letting the thickness or the upper layer equal 0.5 m. Note that layers are numbered from the bottom in the *WINDS* model; thus, the upper layer (below the evaporation layer) is layer 4.

In order to calculate the irrigation frequency and amount, calculate RAW.

$$AWC = \theta_{FC} - \theta_{PWP} = 0.2 - 0.1 = 0.1$$
$$TAW = AWCz = 0.1(2.0m) = 0.2m$$
$$RAW = TAW\ MAD = 0.2m(0.35) = 0.07m = 70mm.$$

Thus, with no leaching, irrigation takes place every 7 days and adds 70 mm to the root zone.

Calculate initial soil water salinity if the field is at field capacity and the saturated paste extract EC is 1.034 dS/m.

$$EC = EC_e\frac{\theta_{sat}}{\theta_{FC}} = (1.034)\left(\frac{0.387}{0.2}\right) = 2\ dS/m$$

The ET from each layer is calculated based on the percent removal from each layer. For example, d_{ET} from layer 4 is ET_{frac-4} d_{ET} = 0.4 (0.01 m/d) = 0.004 mm/d.

The problem specified two scenarios: zero leaching fraction and 1.15 leaching fraction. The following calculations are made for zero leaching fraction.

Day 1: Layer 4 (upper layer)

Calculate water content at the end of day 1

$$\begin{aligned}\Delta d_{cv-4} &= i - d_{seepage-4} - ET_{frac-4} d_{ET} \\ &= 0 - 0 - 0.4(0.01m) = -0.004m \\ \Delta\theta &= \Delta d_{cv-4}/\Delta z = -0.004m/0.5m = -0.008 \\ \theta_{final} &= \theta_{initial} + \Delta\theta = 0.2 - 0.008 = 0.192\end{aligned}$$

Calculate EC after the first day

$$EC_{final} = \frac{i\ EC_{iw} - d_{seepage\text{-}4}\ EC_{initial} + EC_{initial}\ \Delta z\, \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$EC_{final} = \frac{0 - 0 + 2.0\ (0.5)\ (0.2)}{0.5\ (0.192)} = 2.083\ dS/m$$

Day 1: Layer 3

Calculate water content at the end of day 1

$$\begin{aligned}\Delta d_{cv-3} &= d_{seepage-4} - d_{seepage-3} - ET_{frac-3} d_{ET} \\ &= 0 - 0 - 0.3(0.01m) = -0.003m \\ \Delta\theta &= \Delta\theta_{cv-3}/\Delta z = -0.003m/0.5m = -0.006 \\ \theta_{final} &= \theta_{initial} + \Delta\theta = 0.2 - 0.006 = 0.194\end{aligned}$$

Calculate EC after the first day

$$EC_{final} = \frac{d_{seepage\text{-}4}\ EC_4 - d_{seepage\text{-}3}\ EC_{initial} + EC_3\ \Delta z\, \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$EC_{final} = \frac{0 - 0 + (2.0)\ (0.5)\ (0.2)}{(0.5)\ (0.194)} = 2.062\ dS/m$$

Day 2: Layer 4 (upper layer)

Calculate water content at the end of day 2

$$\begin{aligned}\Delta d_{cv-4} &= i - d_{seepage-4} - ET_{frac-4} d_{ET} \\ &= 0 - 0 - 0.4(0.01m) = -0.004m \\ \Delta\theta &= \Delta d_{cv-4}/\Delta z = -0.004m/0.5m = -0.008 \\ \theta_{final} &= \theta_{initial} + \Delta q = 0.192 - 0.008 = 0.184\end{aligned}$$

Calculate EC

$$EC_{final} = \frac{i\ EC_{iw} - d_{seepage\text{-}4}\ EC_{initial} + EC_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$EC_{final} = \frac{0 - 0 + 2.08\ (0.5)\ (0.192)}{0.5\ (0.184)} = 2.17\ dS/m$$

Day 2: Layer 3

Calculate water content at the end of day 2

$$\begin{aligned}\Delta d_{cv-3} &= d_{seepage-4} - d_{seepage-3} - ET_{frac-3} d_{ET} \\ &= 0 - 0 - 0.3(0.01m) = -0.003m \\ \Delta\theta &= \Delta d_{cv-3}/\Delta z = -0.003m/0.5m = -0.006 \\ \theta_{final} &= \theta_{initial} + \Delta\theta = 0.2 - 0.006 = 0.194\end{aligned}$$

Calculate EC

$$EC_{final} = \frac{d_{seepage\text{-}4}\ EC_4 - d_{seepage\text{-}3}\ EC_{initial} + EC_3\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$EC_{final} = \frac{0 - 0 + (2.063)\ (0.5)\ (0.194)}{(0.5)\ (0.188)} = 2.13\ dS/m$$

Day 3: Layer 4

Irrigation depth 0.07 m is applied on this day. The infiltration depth far exceeds the capacity of layer 4 so most of the water infiltrates to layer 3. The mass balance equation for salts must be modified when water from a large irrigation event or storm passes completely through the layer. As stated previously, the rationale is that all nitrate from the irrigation water or storm is mixed with the nitrogen in the layer, and the mixed concentration is the final concentration in the layer.

The depth of seepage from layer 4 to layer 3 is calculated as follows:

$$\begin{aligned}& i - ET_{layer-4} - (\Delta z\ \theta_{FC} - \ \Delta z\ \theta_{initial}) \\ &= 0.07m - 0.004m - (0.2(0.5m) - 0.184(0.5m)) \\ &= 0.058m\end{aligned}$$

Calculate EC

$$EC_{final} = \frac{\text{mass of salts}}{\text{volume of water}} = \frac{i\ EC_{iw} + EC_{initial}\ \Delta z\ \theta_{initial}}{i - ET_{layer} + \Delta z\ \theta_{initial}}$$

$$\begin{aligned}& EC_{final} \\ &= \frac{(0.07\ \text{m})\ (1\ \text{dS/m}) + 2.17{*}0.5\ (0.184)}{0.07m - (10\, mm)\ (0.4)/(1000\, mm/m) + 0.5\ (0.184)} \\ &= 1.71\, dS/m\end{aligned}$$

Day 3: Layer 3

As with layer 4, the modified equation must be used. In this case, the final salinity of layer 4 is the seepage concentration instead of the initial salinity of layer 4.

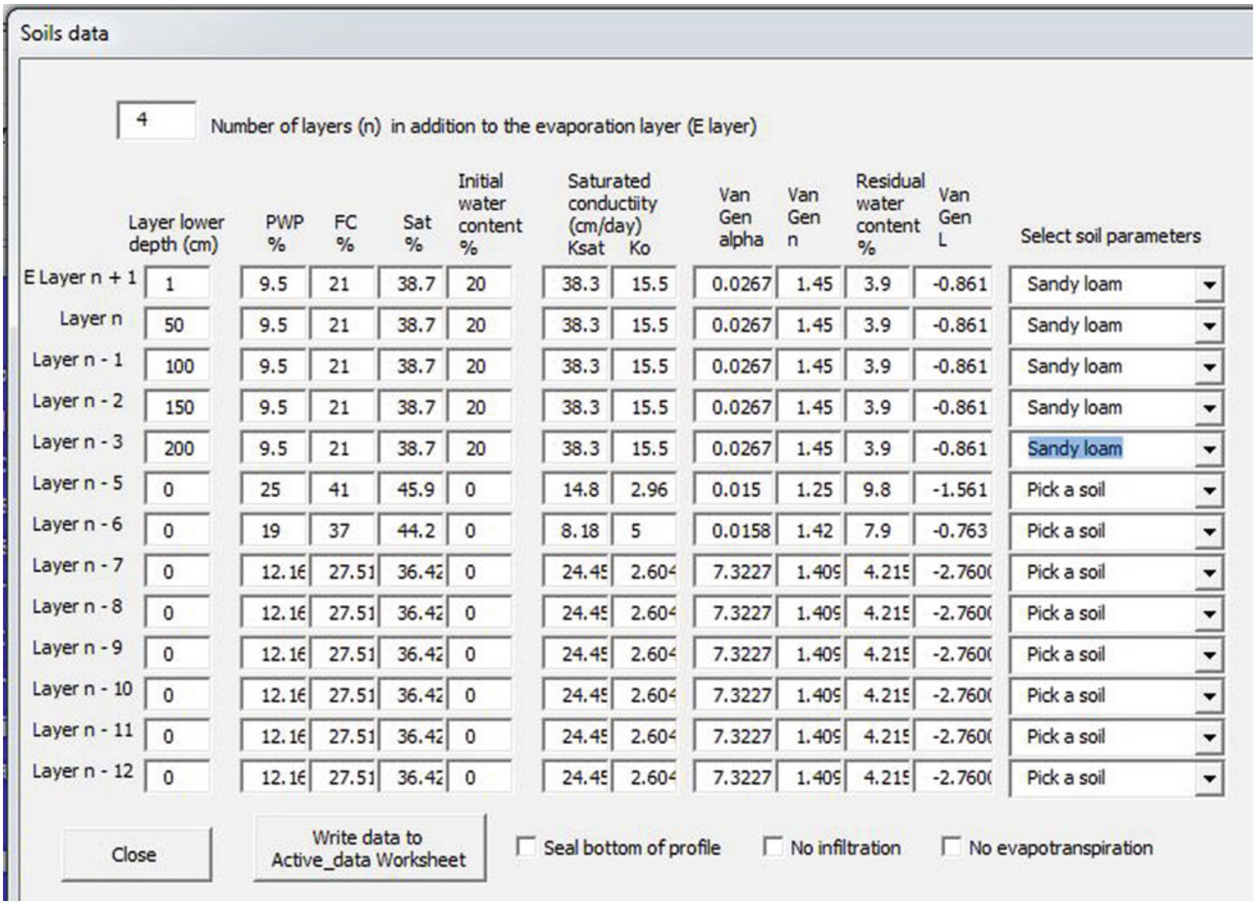


Fig. 26.4 *Soils* dialog box with 4 layers plus evaporation layer parameters

$$\mathrm{EC_{final}} = \frac{\mathrm{d_{seepage\text{-}4}}\ \mathrm{EC_4} + \mathrm{EC}_{initial}\ \Delta z\ \theta_{initial}}{i - ET_{layer} + \Delta z\ \theta_{initial}}$$

$$\mathrm{EC_{final}} = \frac{(0.058\ \mathrm{m})\ (1.71\ \mathrm{dS/m}) + 2.13{*}0.5\ (0.188)}{0.058\ m - 10\ mm\ (0.3)/(1000\ mm/m) + 0.5\ (0.188)} = 2.01\ dS/m.$$

The same calculations are made in the *WINDS* model. The process of setting up the *WINDS* model begins by defining the soil parameters. The *Soil_data* worksheet has typical soil parameters for different soil textures. A button on the *Soil_data* worksheet triggers the *Soils* dialog box (Fig. 26.4). In this case, field capacity, permanent wilting point, and saturated water content are similar to sandy loam so the sandy loam soil is selected and then slightly modified to have the parameters in this example. Only the upper four layers and the evaporation layer are defined. Only the left five parameters are used in this example. The right six parameters will be required in later chapters for water movement in response to energy gradients. In order to ignore the evaporation layer, the evaporation layer thickness is set at 1.0 cm (small).

Click the *Write data to Active_data worksheet* button. Soil parameters are stored in cells B40:B229 in the *Active_data* worksheet. The plant growth phases are defined in cells B3:B18 (Fig. 26.5). For this example, the root zone is defined as 1.0 m depth from the beginning to the end of the growing season. Kcb is also defined as 1.0 for the entire growing season because the crop coefficient is 1.0 for the entire period of the example.

Once the soils, plant, and salinity information are defined, all information in column B can be written to one or more field locations in the *Crop_data* worksheet. The target locations are entered in cells G13:G14. The information is written to locations 1 and 2 by clicking the *Copy data to Crop_data* button.

The fraction of evapotranspiration removed from each layer is defined in the *ET_fractions* worksheet (Fig. 26.6). In this case, there are four layers (in the root zone) during the

Fig. 26.5 *Active data* worksheet plant information

Fig. 26.6 ET_fractions worksheet with fractions defined for a 4 layer soil

	A	B	C	D	E	F	G
1			2L	3 L	4 L	5 L	6 L
2	Evap	1	0	0	0	0	0
3	Upper	50	0	0	0.4	0	0
4	Upper - 1	100	0	0	0.3	0	0
5	Upper - 2	150	0	0	0.2	0	0
6	Upper - 3	200	0	0	0.1	0	0
7	Upper - 4	110	0	0	0	0	0

entire simulation so only the 4 L column needs to be defined. No water is removed from the evaporation layer.

The reference evapotranspiration is set at 10 mm/day for all days in column D in the *Active_year_weather* worksheet (Fig. 26.7). All other columns are ignored in this simulation.

The irrigation rate is defined in the *IRR_01* worksheet (Fig. 26.8), which defines irrigation days and depths for each section of a field. In this case, the reference irrigation depth is 70 mm every 7 days. The field location Sec_1 (location 1), which has no leaching fraction, has the same application depth as the reference depth. Thus, the ratio entered in column C is 1.0. However, section 2 (Column D) has a value of 1.176 to represent the 15 % leaching fraction, as calculated in Example 4.6. It is easy to imagine that this approach can be used to specify many infiltration depths in an agricultural field.

The simulations are run from the *Main* worksheet (Fig. 26.9). Field locations in the simulation are defined in cells E2 and G2 (field positions 1 and 2). Dates are defined in row 3. Cell C5 is set to FALSE in order to ignore rainfall. Cell E5 is set to TRUE in order to include a salinity simulation. The irrigation strategy is defined as 1 (defined dates and depths in *IRR_01* worksheet) in the combobox in cell A9. The crop coefficient calculation method is defined as 5 (crop coefficient always equals 1.0 with no evaporation from the evaporation layer) in the I18 combobox. Cell I37 is defined as TRUE in order to prevent ET_fraction adjustment based on water content differences between layers, and cell I39 is defined as TRUE in order to prevent water movement between layers between irrigation events based on energy differences (Richards equation).

Once all parameters are set, the Run button is clicked. The *Get data* combobox located at cell L5 (Fig. 26.9) retrieves the simulation data from the *C01* worksheet (Section 1) and places it in the *Water content, Nitrogen* and *Salinity* worksheets, where the data can be viewed in predefined graphs. Click the *View water content* button in order to go to the *Water content* worksheet. There are many graphs available in the *Salinity, Nitrogen* and *Water content* worksheets. A dialog box (Fig. 26.10) allows the user to select between graphs. The Water content graph is selected. The dialog box also allows the user to specify the axis limits and to select which layers are displayed. The water content in the upper four layers are shown in Fig. 26.10.

	Chap 26 simulation				1			1.00
DOY	RHmin	WS	ET0 (mm)	Rain (mm)	Tmax ©	Tmin ©	Rain time (hr)	
1	28.9	1	10	0	18.8	2.5	1	
2	50	1.6	10	3.3	17	8.6	1	
3	47.2	2	10	10.16	19.8	10	1	
4	52.1	2.2	10	1.02	15.2	6.8	1	
5	39.3	1	10	0	12.5	1.5	1	
6	31	1.5	10	0	14.4	-1.6	1	
7	14.4	1.3	10	0	19.2	0.2	1	
8	23.9	1.4	10	0	21.6	4.6	1	
9	29.1	1	10	0	21.4	2.6	1	
10	19.6	0.45	10	0	22.3	4.8	1	
11	15.3	2.2	10	0	21.5	10.4	1	
12	38.3	3.3	10	0	11.7	3.2	1	
13	21.5	1.1	10	0	16	-2.3	1	
14	13.2	1	10	0	20.4	3.1	1	
15	11.1	1	10	0	21.7	-1.9	1	
16	9.6	0.9	10	0	25.6	-1.2	1	

Go to WINDS Go to Main

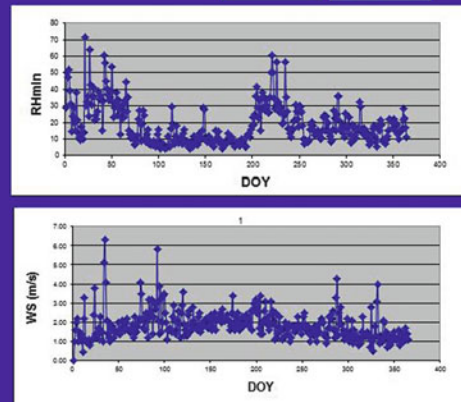


Fig. 26.7 Active year weather worksheet with 10 mm/d reference ET specified in column D

Fig. 26.8 The *IRR_01* worksheet with irrigation dates and depths defined

DOY	Ref (mm)	Sec_1	Sec_2	Sec_3	Sec_4
1					
2					
3	70	1	1.15		
4					
5					
6					
7					
8					
9					
10	70	1	1.15		
11					
12					
13					
14					
15					
16					
17	70	1	1.15		

The water contents vs. time can be found in columns AB:AF in the *Water content* worksheet. The calculated water contents are the same as the manually calculated values in this example in layers 3 and 4 for the first 3 days. The evaporation layer water content (column AF) remains at field capacity because the evaporation and evapotranspiration rates were set to zero for the evaporation layer. Thus, irrigation water just passes through the evaporation layer. Because the initial soil water salinity in the evaporation layer was set to be the same as the irrigation water salinity, the evaporation layer has no effect on the solution in this problem. The 15 % leaching fraction simulation (worksheet *C02*) has the same pattern of water content vs. time as the no leaching alternative (Fig. 26.10 and worksheet *C01*). The reason for this is that the same evapotranspiration pattern takes place and the soil is filled back to field capacity during irrigation events in both cases. However, there is more seepage water with the 15 % leaching fraction.

The salinity parameters can be specified in the *Salinity* dialog box accessed from the Salinity button in the *Active_data* worksheet (Fig. 26.11). The salinity data is written to cells B250:B288 in the *Active_data* worksheet. The initial salinity is set at 1.033 dS/m saturated paste extract salinity for this example. Because saturation is

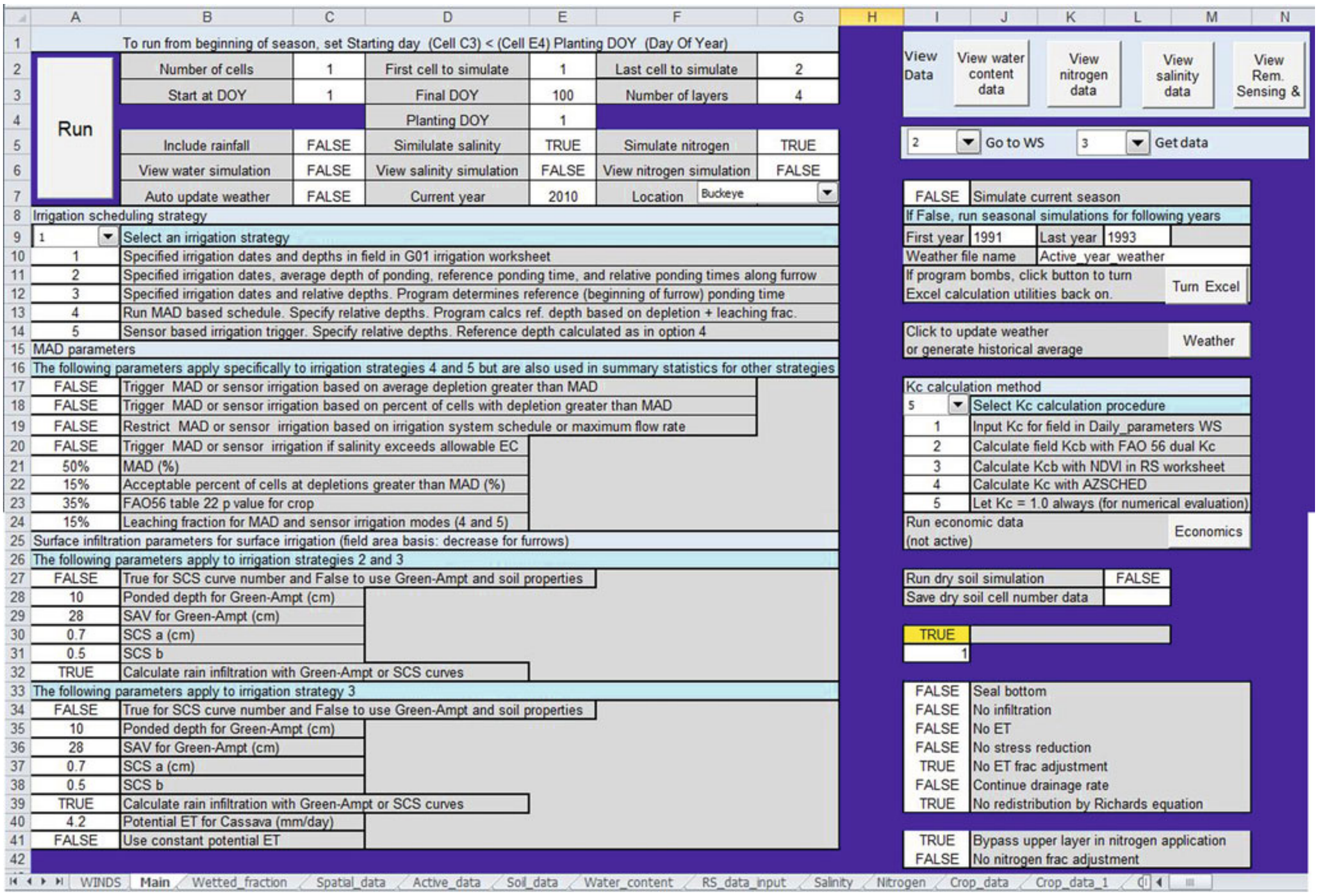


Fig. 26.9 The *Main* worksheet set up for Chapter 26 simulations

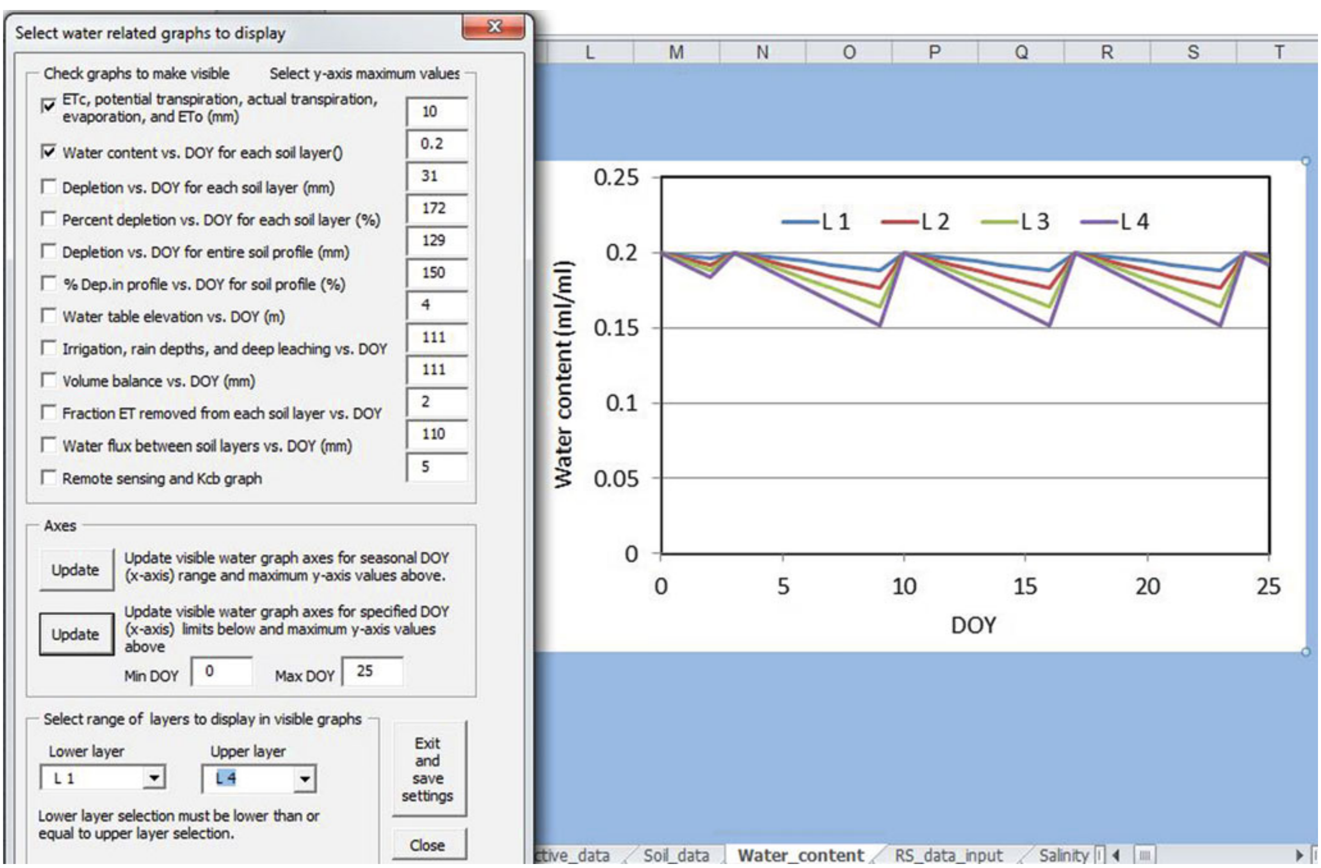


Fig. 26.10 Water Content worksheet with dialog box and water content graph

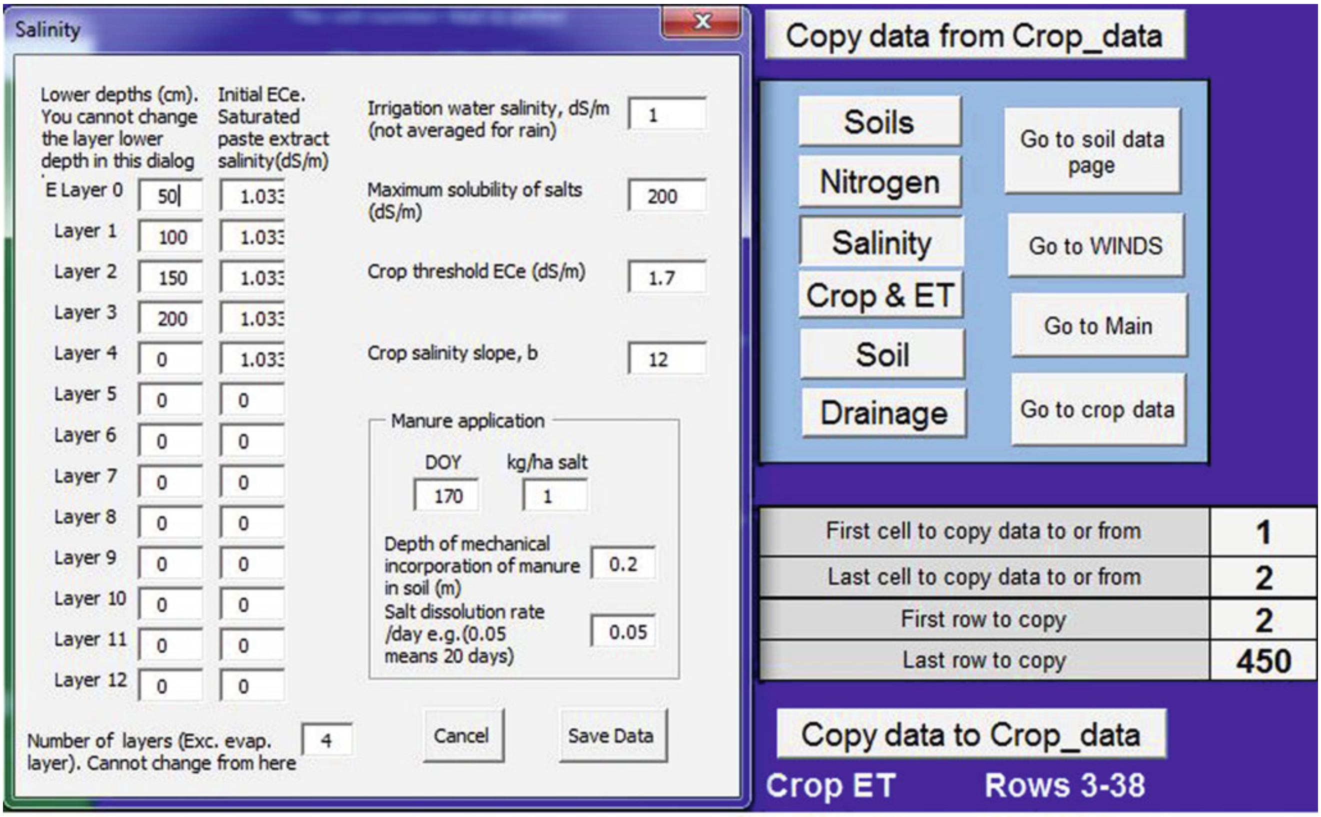


Fig. 26.11 Salinity dialog box with parameters for Example 26.5

38.7 % and field capacity is 20 %, this sets the initial soil water salinity at 2.0 dS/m.

Click the *Go to Main* button and then click the *View salinity* button in the *Main* worksheet in order to go to the *Salinity* worksheet. The Salinity worksheet also has a dialog box that allows the user to select between graphs (Fig. 26.12). The salinities after 100 days are 2-, 3.5-, 6.5-, and 7-dS/m in layers 1 to 4, respectively. The salinity increases during each cycle as the water content decreases. This is the result of the fact that the water is extracted but the salinity remains in the soil.

This example illustrates the fact that soil salinity can increase significantly within 100 days. In order to look at the 15 % leaching fraction scenario, go to the Main worksheet and click 2 in the *Get_data* combobox. The calculated salinity values are the same as the manual calculations in the first part of this example. The salinity curves for 15 % leaching fraction are shown in Fig. 26.13.

The steady state salinity (Example 4.6) values with 15 % leaching fraction (Example 26.4) were 1.5-, 2.5-, 4.3-, and 6.7-dS/m. The upper 3 layers have reached these equilibrium concentrations after 100 days while the lower layer (layer 1) is still approaching the final steady state concentration.

One of the most important checks for accuracy in simulation models is the mass balance. Even if some processes are modeled with some incorrect assumptions, a validated mass balance is the first step towards a reasonable solution; on the other hand, letting mass vanish into thin air guarantees an inaccurate solution. The mass balance verification in the *WINDS* model is based on the fact that the sum of sources and sinks should equal the change in storage. The volume balance for water is found in the *Water content* worksheet and can be accessed with the dialog box in the *Water content* worksheet. Figure 26.14 shows that the sum of sources and sinks equals the change in storage so the volume balance is verified. The reason that the sum of sources and sinks is less than 70 on irrigation days is that some water was lost to evapotranspiration.

The salinity mass balance also shows that salts are conserved in the model (Fig. 26.15). The salt balance is negative on the third day because irrigation was conducted before it was required; thus, leaching greatly exceeded 15 %.

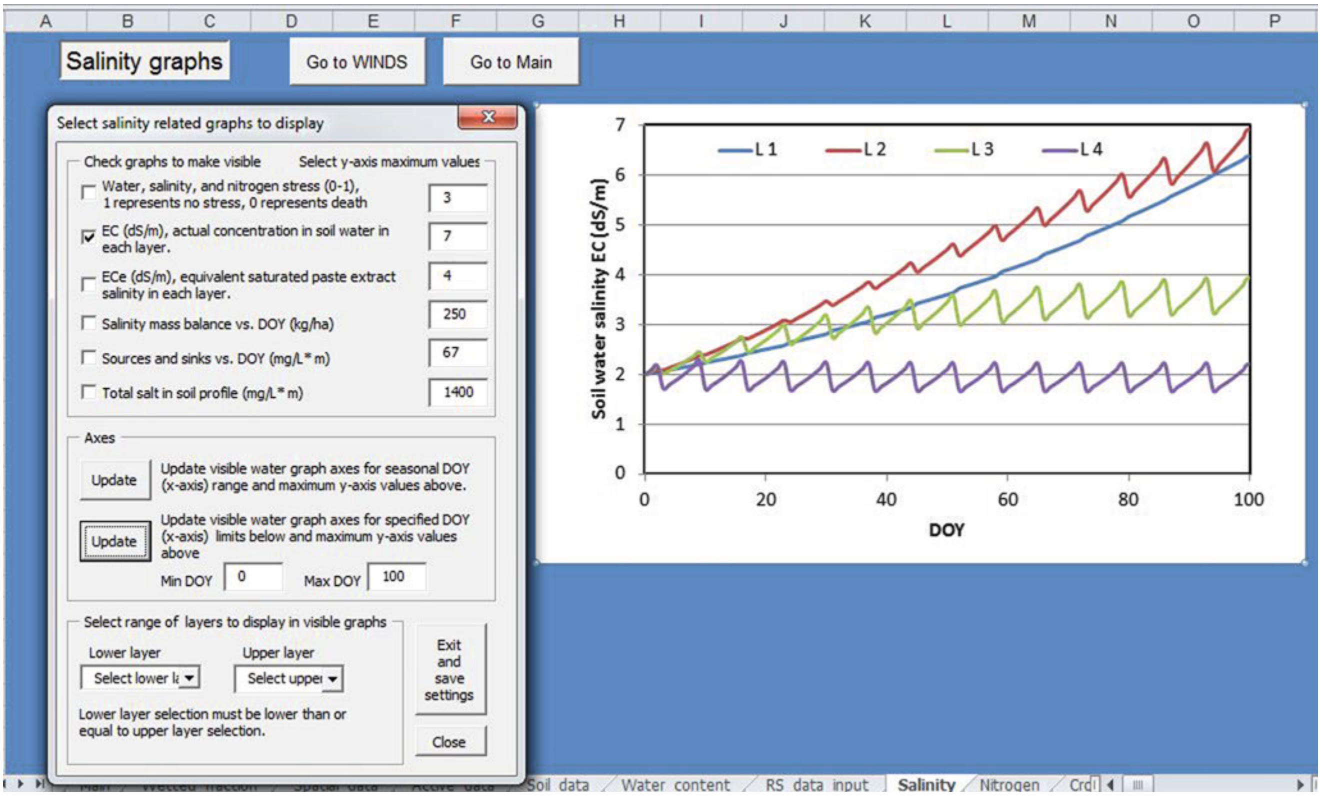


Fig. 26.12 *WINDS* model simulation of salinity for 100 days with no leaching in Example 26.5

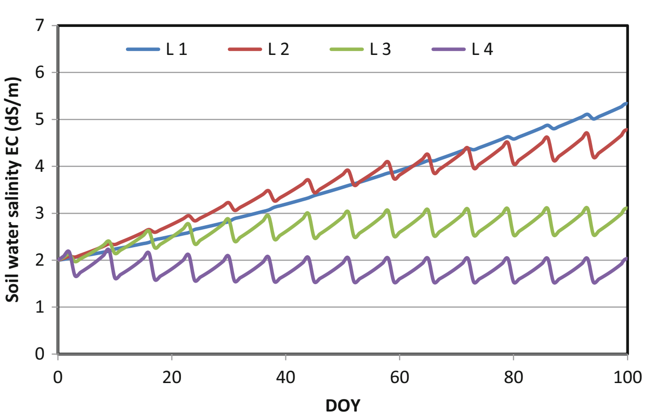


Fig. 26.13 *WINDS* model simulation of Example 26.5 salinity for 100 days with 15 % LF in Example 26.5

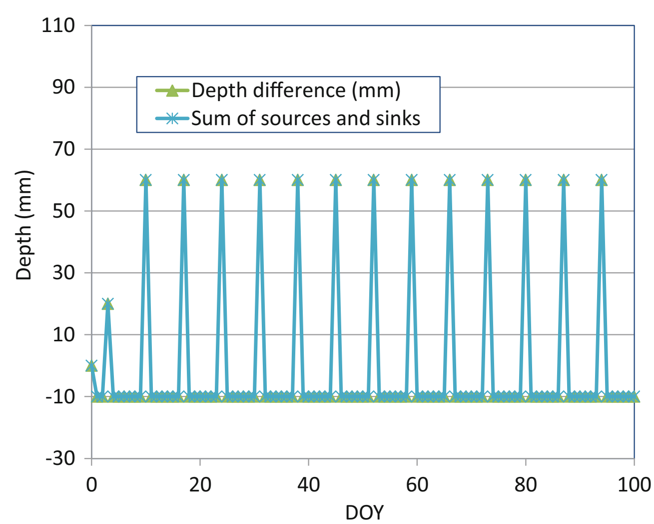


Fig. 26.14 Mass balance for water content in the *WINDS* model for Example 26.5

Nitrate Mass Balance Model

Nitrate has a negative charge; thus, we can assume that nitrate is not absorbed by soil particles and is in the soil water solution. The following derivation of the soil nitrate model is similar to the soil salinity model; however, there are reactions terms.

The sources, sinks, and flux of nitrate in a layer are shown in Fig. 26.16. The nitrate mass is typically reported as only the mass of elemental nitrogen rather than the entire nitrate molecule. This is commonly called nitrate-N (NO_3-N) and is represented by the letter N in this chapter.

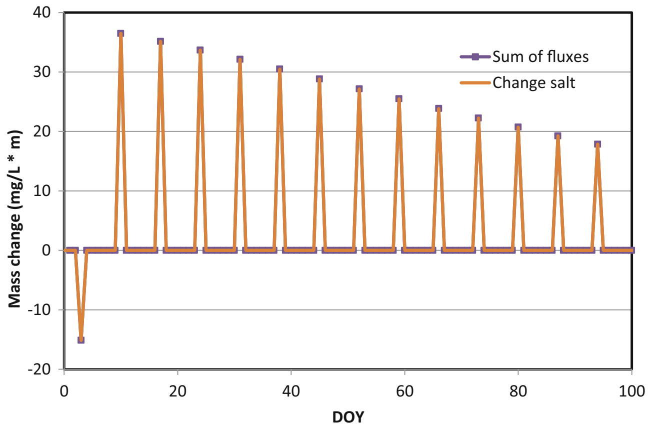


Fig. 26.15 Mass balance for salinity in the *WINDS* model for Example 26.5

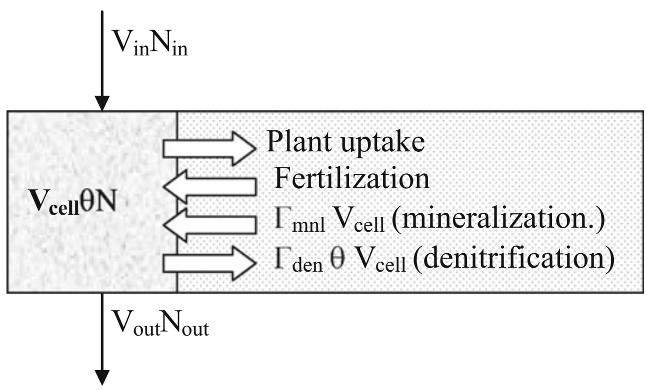


Fig. 26.16 Nitrate (NO_3-N) mass balance in root zone

As with salinity, the mass of N in the water in a layer can be calculated as mg/L m.

$$m_{N-layer} = \Delta z N\theta \tag{26.29}$$

where

$m_{N\text{-layer}}$ = mass of NO_3-N within the layer, mg/L m.

The change of N mass within the control volume is

$$\begin{aligned} dm_{N-layer} &= \Delta(N\ \Delta z\ \theta) \\ &= N_{final}\Delta z\ \theta_{final} - N_{initial}\ \Delta z\ \theta_{initial} \end{aligned} \tag{26.30}$$

where

$dm_{N\text{-layer}}$ = change in mass of NO_3-N, mg/L_{soil} m.
$N_{initial}$ = initial NO_3-N concentration, mg/L_{water},
N_{final} = final NO_3-N concentration, mg/L_{water},

The nitrate flux terms are the product of water flux and the concentration.

$$m_{in} = d_{in}N_{in} \quad mg/Lm \tag{26.31}$$

$$m_{out} = d_{out}N_{initial} \quad mg/Lm \tag{26.32}$$

where

N_{in} = NO_3-N concentration in water entering the layer, mg/L_{water}
$N_{initial}$ = Initial NO_3-N concentration in layer, mg/L_{water},

The reaction terms include mineralization, denitrification, plant uptake, and fertilization. The change in nitrate mass due to mineralization is the product of the mineralization rate (Γ_{mnl} from Eq. 25.3) per volume of soil, time, and the depth of the layer.

$$\begin{aligned} m_{min} &= \Delta z\ \Gamma_{min}\ \Delta t = (m)(mg/L_{soil}/d)(d) \\ &= mg/Lm \end{aligned} \tag{26.33}$$

where

Γ_{min} = rate of reaction, mg/L_{soil}/d.
m_{min} = mass added to the layer by mineralization, mg/L_{soil} m
Δt = time step, days.

The change in nitrate mass due to denitrification is calculated with Γ_{den} from Eq. 25.15.

$$m_{den} = \Delta z\ \Gamma_{den}\Delta t \tag{26.34}$$

The change in nitrate mass due to fertilization is calculated by dividing the kg/ha application rate by 10.

$$\begin{aligned} m_{fer} &= \frac{App\ rate(kg/ha)}{10} \\ &\Rightarrow \left(\frac{kg}{ha}\right)\left(\frac{10^6\ mg}{kg}\right)\left(\frac{ha}{10^4\ m^2}\right)\left(\frac{m^3}{10^3\ L}\right) \\ &= mg/L_{soil}\ m \end{aligned} \tag{26.35}$$

The change in nitrate mass due to plant uptake is calculated by dividing the kg/ha plant nitrate uptake by 10.

$$m_{upt} = \frac{N_{upt}(kg/ha)}{10} \Rightarrow mg/L_{soil}\ m \tag{26.36}$$

where
m_{upt} = mass of nutrients taken up by crop, mg/L m,
N_{upt} = Nitrate removed by the crop, kg/ha.
The continuity equation for mass of NO_3-N within a layer is

$$\begin{aligned} dm_{N-layer} &= d_{in}N_{in} - d_{out}N_{initial} + m_{min} - m_{den} \\ &+ m_{fer} - m_{upt} \end{aligned} \tag{26.37}$$

Substitute Eq. 26.37 into Eq. 26.30

$$\begin{aligned} & N_{final}\ \Delta z\ \theta_{final} - N_{initial}\Delta z\ \theta_{initial} \\ & \quad = d_{in}N_{in} - d_{out}N_{initial} + m_{min} - m_{den} + m_{fer} \\ & \qquad - m_{u\,pt} \end{aligned} \tag{26.38}$$

Equation 26.38 is rearranged to solve for final nitrogen content within the soil profile.

$$N_{final} = \frac{d_{in}\ N_{in}\ -\ d_{out}\ N_{initial}\ +\ m_{min} - m_{den}\ +\ m_{fer} - m_{u\,pt}\ +\ N_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}} \tag{26.39}$$

As with the salinity model, if infiltration into the layer from above exceeds the available water storage capacity in the layer (the product of field capacity and layer depth), then Eq. 26.39 is not valid. In this case, the weighted average concentration of the layer water and the infiltrating water from the above layer leaches to the next layer. Thus, the final NO_3-N concentration as well as the leachate NO_3-N concentration would be

$$\begin{aligned} N_{final} = & (i\ N_{iw} + N_{initial}\ \theta_{initial}\Delta z + m_{min} - m_{den} \\ & + m_{fer} - m_{u\,pt})/(i + \theta_{initial}\Delta z - ET - E). \end{aligned} \tag{26.40}$$

Example 26.5 For the parameters in Example 26.4 (no leaching fraction), make sample calculations of nitrate concentration during the first 3 days for the upper layer (below the 1 cm evaporation layer). Use the following nitrogen model parameters. Then use *WINDS* to calculate nitrate concentration for the first 100 days of the year. Apply 20 kg/ha fertilizer on DOY 1, to be incorporated into the upper layer. Irrigate on DOY 3, and then irrigate every 7 days thereafter. Ignore the 1 cm evaporation layer. Plant uptake of nitrogen is 50 kg/ha, with no uptake during the first 30 days and uniform uptake during the last 70 days of the growing seasons. The *WINDS* model parameters are set as shown in Fig. 26.17.

Parameter	Value
K_{mnl}	0.0002
θlow	0.15
θhigh	0.22
Q_{temp}	3
On-max	3000
α	0.025
K_{den}	0.002
Frac NO3 uptake	0.75
Fertilizer dissolution rate	1.0/day
Nitrate conc. in irrigation	10 mg/L

(*continued*)

Parameter	Value
tm	100 days
Tbar	21.0 C
A0	17.1 C
Nitrogen requirement	50 kg/ha (no uptake until development phase is over)

Initial nitrate concentrations (mg/kg soil) are

Evap layer	1.2
Layer 4	35
Layer	30
Layer 2	25
Layer 1	20

Day 1: Upper layer (layer 4)

Calculate initial nitrate concentration in layer 1 by converting from mg/kg soil to mg/L water. The initial water content is 20 %

$$\begin{aligned} N &= N\_soil/\theta(1 - \theta_{SAT})(2.65) \\ &= 35mg/kg/0.2(1 - 0.387)(2.65) = 284mg/L \end{aligned}$$

Calculate average soil profile temperature on day 1.

$$T(1) = 21.1 + 17.1\sin\left(\frac{2\pi}{365}(t - 100)\right) = 4.15\ C$$

Calculate NO_3-N mineralization in layer 1
$\theta = 0.20$, $\theta_{low} = 0.15$, thus $f_{mn\theta} = 1.0$

$$f_{temp} = Q_{10}^{\left(\frac{T - t_b}{10}\right)} = 3^{\left(\frac{4.15 - 20}{10}\right)} = 0.175$$

$$\rho = \rho_p(1 - \phi)\ = 2.65(1 - 0.387) = 1.62$$

$$O_n = O_{n_{max}} e^{-0.025z} = 3{,}000\ e^{-0.025\ *25} = 1{,}606\ \mu g/g$$

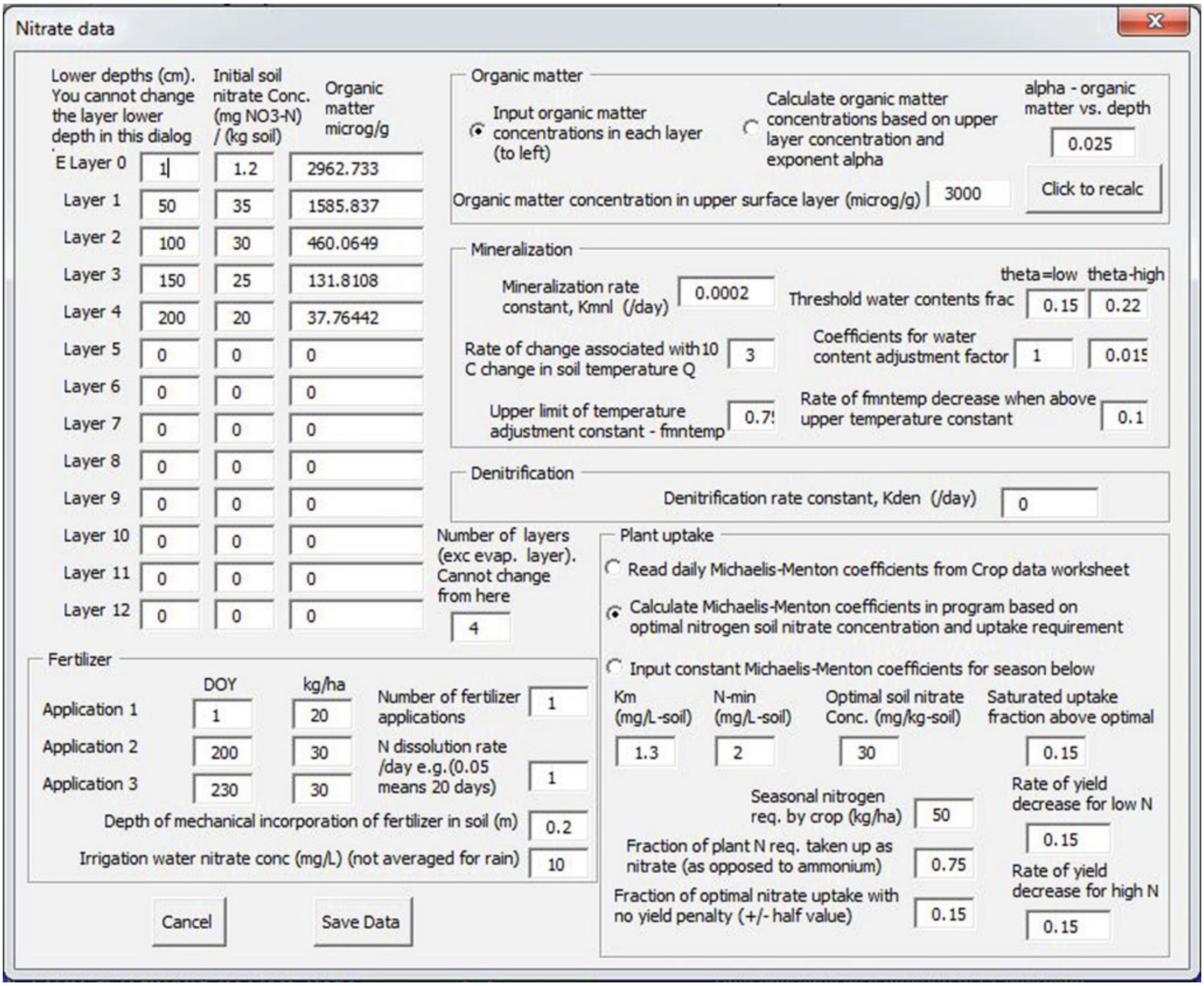


Fig. 26.17 Nitrogen specifications in *WINDS* model for Example 26.5

$$\begin{aligned}\Gamma_{mnl} &= K_{mnl}\, f_{mnl\theta}\, f_{temp}\, \rho O_n \\ &= 0.0002(1.0)(0.175)(1.62)(1,606) \\ &= 0.09106\ \text{mg}/\text{L}_{soil}/\text{day}\end{aligned}$$

$$\begin{aligned}m_{mnl} &= \Gamma_{mnl}\Delta z\ \Delta t = 0.9106(0.5\ \text{m})(1\ \text{day}) \\ &= 0.0455\ \text{mg}/\text{L}_{soil}\ \text{m}\end{aligned}$$

Calculate denitrification

$\theta = 0.20$ and $\theta_{sat} = 0.387$. Because no denitrification takes places is less than 60 % of pore space is filled with water, denitrification does not take place

Calculate fertilizer addition. The dissolution rate is 1.0. This means that all fertilizer will be added to the soil on the day after fertilization in the *WINDS* model.

There is no plant nitrogen uptake at the beginning of the season.

The water content decreases to 0.192

Calculate new concentration

$$N_{final} = \frac{d_{in}\ N_{in} - d_{out}\ N_{initial} + m_{min} - m_{den} + m_{fer} - m_{upt} + N_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$N_{final} = \frac{(0)N_{in} - (0)N_{initial} + 0.0455 - 0 + 0 - 0 + 284\ (0.49)\ (0.2)}{0.49\ (0.192)} = 296\ mg/L$$

Day 2: Upper layer (layer 4)

Temperature remains the same; thus, NO_3-N mineralization remains the same since it is a zero order equation (not dependent on nitrate concentration), $m_{mnl} = 0.0455$

Denitrification remains zero.

Calculate fertilizer addition. The dissolution rate is 1.0. This means that all fertilizer applied on the previous day is added to the soil this day.

$$m_{fer} = \frac{App\ rate(kg/ha)}{10} = \frac{20\ kg/ha}{10} = 2\ mg/L_{soil}\ m$$

Calculate new concentration

$$\mathrm{N_{final}} = \frac{\mathrm{d_{in}\ N_{in} - d_{out}\ N_{initial} + m_{min}} - m_{den} + m_{fer} - m_{upt} + \mathrm{N}_{initial}\ \Delta z\ \theta_{initial}}{\Delta \mathrm{z}\ \theta_{final}}$$

$$\mathrm{N_{final}} = \frac{(0)\mathrm{N_{in}} - (0)\mathrm{N_{initial}} + 0.0455 - 0 + 2 - 0 + 296\ (0.49)\ (0.192)}{0.49\ (0.184)} = 331\ mg/L$$

Day 3: Upper layer (layer 4)

This day has a 0.07 m depth irrigation. Most water passes through since initial water content is 0.184, and 0.2 is field capacity; thus, the soil can only hold 0.016*0.5 m = 0.008 m → 0.07 – 0.008 = 0.062 passes through layer 1. The nitrate concentration in irrigation water (and in the evaporation layer) is 10 mg/L. When water from a large irrigation event or storm passes completely through a layer, the following mass balance equation can be modified as follows. This equation calculates the mixed concentration, and is the concentration of nitrogen in the water that seeps to the next layer.

$$\mathrm{N_{final}} = \frac{\mathrm{d_{in}\ N_{in} + m_{min}} - m_{den} + m_{fer} - m_{upt} + \mathrm{N}_{initial}\ \Delta z\ \theta_{initial}}{d_{\mathrm{in}} - ET_{layer} + \Delta \mathrm{z}\ \theta i_{initial}}$$

$$\mathrm{N_{final}} - \frac{(0.07\ \mathrm{m})(10\ \mathrm{mg/L}) + 0.0455 - 0 + 0 - 0 + 331\ (0.49)\ (0.184)}{0.07m - 10\ mm{*}0.4/(1000\ mm/m) + 0.49\ \mathrm{m}\ (0.184)} = 196\ mg/L$$

The 196 mg/L in layer 4 is the same concentration reported in the *WINDS* model Nitrogen page in cell AE3. The *WINDS* model nitrogen page also has many graphs and a dialog box to select from them. The mass balance graph shows that nitrate is conserved. The fertilizer addition on day 2 resulted in a gain of total nitrate, and the drainage event on day 4 resulted in a loss. The mineralization increased later in the season when the temperature increased. The irrigation events added nitrate every seven days (Fig. 26.18). A closer look shows that mineralization increased during the season, but that plant uptake of nitrogen began at DOY 30 and decreased the overall increase in nitrogen per day (Fig. 26.19).

The leaching of nitrate to the lower layers over time (Fig. 26.20) is similar to the leaching of salinity over time (Fig. 26.12).

Although the total average nitrogen in the soil profile increases, much of it is leached below the upper layers.

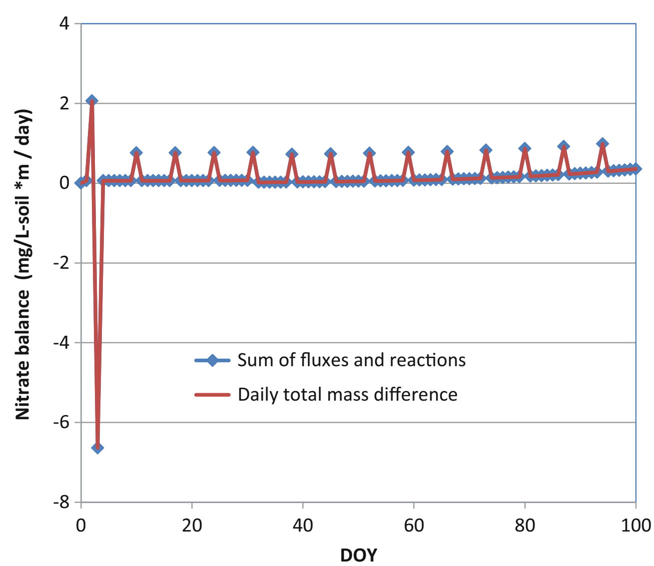


Fig. 26.18 Nitrate mass balance for Example 26.6

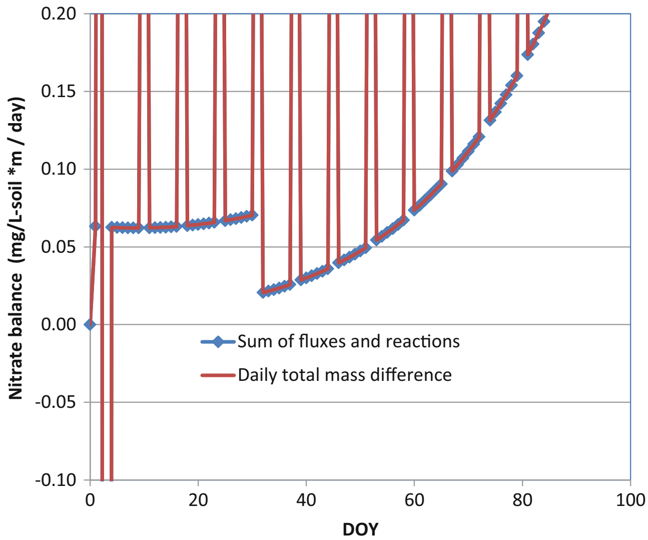


Fig. 26.19 Nitrate mass balance for Example 26.6

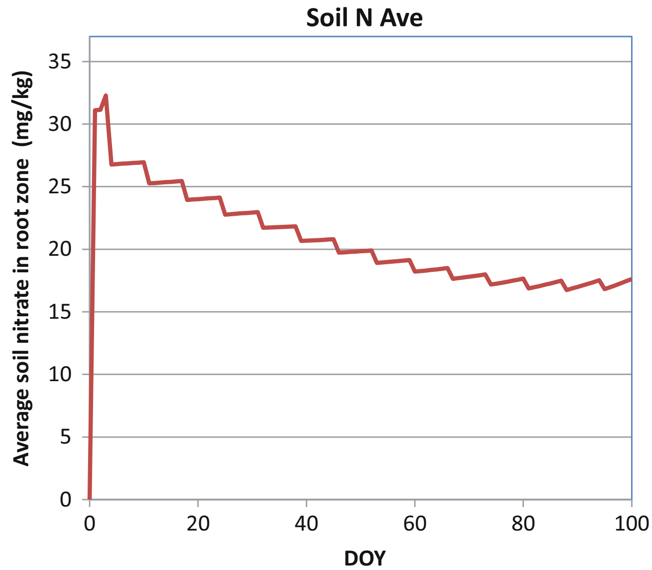


Fig. 26.21 Average weighted nitrate concentration versus time with weights based on fraction of water extraction (root density) in each layer, for Example 26.6

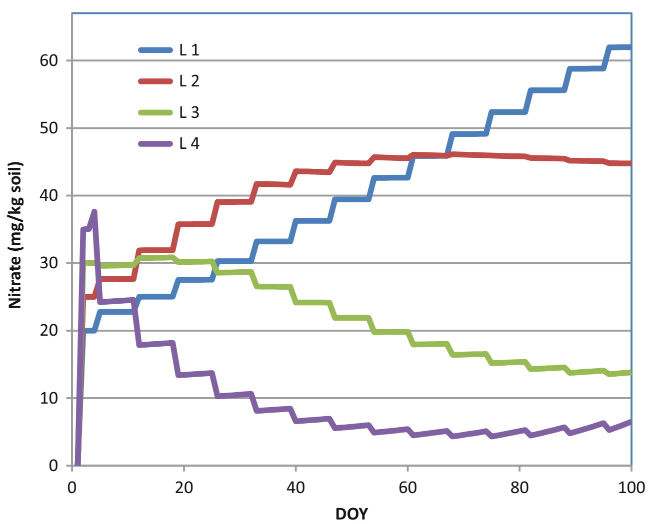


Fig. 26.20 Nitrate concentration in layers for Example 26.6

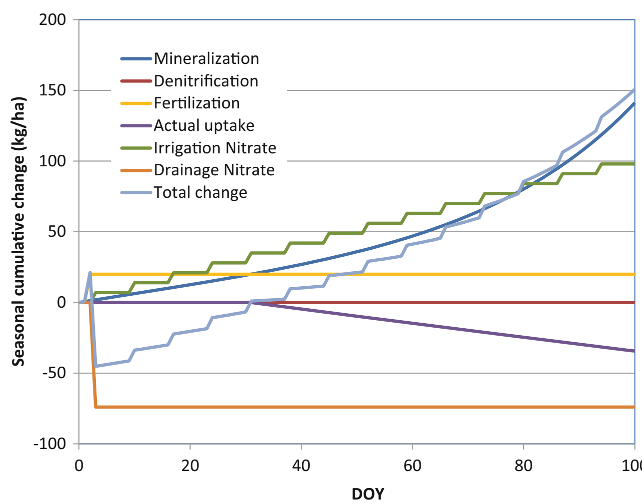


Fig. 26.22 Cumulative change versus time for all nitrate sources and sinks in Example 26.6

Thus, the weighted average nitrate concentration decreases if the weights are based on the fraction of water extraction in each layer (Fig. 26.21). Most of the nitrate in the soil profile has been leached to the lower layers (Fig. 26.20).

The cumulative contribution to the nitrate mass balance of all sources and sinks is shown in Fig. 26.22. The cumulative change due to plant uptake is only 34 kg/ha while the plant nitrogen requirement was 50 kg/ha. This was caused by the fact that only 75 % of the plant nitrogen uptake was nitrate (37.5 kg/ha) and by the uptake being penalized by low nitrate concentration in the upper layers by the Michaelis-Menton equation. The optimal concentration was specified as 30 mg/kg, but the weighted average nitrate concentration dropped below 20 mg/kg; thus, the uptake was reduced. Of course, these types of numbers would need to be generated by experiment for a particular crop. By far, the biggest loss was due to the irrigation event on the third day, when the soil water content was higher than it normally would be just before an irrigation event. This demonstrates the environmental hazard associated with overapplication or mistiming of irrigation events and nitrogen fertilization.

Questions

1. Repeat Example 26.1, but change the infiltration from the first storm to 3 cm, and the field capacity to 0.25. As before, infiltration from the second storm is 4 cm.
2. Redo question 1, but divide the soil into three layers of 0.4 m depth.
3. Redo Example 26.3, but change the upper layer FC is 0.26, and the lower layer FC to 0.24. Also, 70 % of ET is removed from the upper layer and 30 % from the lower layer.
4. Redo Example 26.4 with the WINDS model and by hand, but lower the leaching fraction to 0.05. Make calculations for the irrigation on the third day for the upper two layers by hand. Next, use the WINDS model to calculate EC for 100 days. There are only two field sections in the *WINDS Chapter 26* workbook. The sections are organized with respect to their irrigation zones in the *spatial data* worksheet. Add another G01 section in column C and write "3" in the same row in column. In cell K7, specify that the number of cells is 3 and click the *Make new sections* button. This process adds the C_3 worksheet to the end of the workbook. The next step is to populate the date in the *Crop_data* worksheet for section 3. You can do this in the A*ctive Data* worksheet or just copy the cells from section 2 (column C) to section 3 (column D) in the *Crop_data* worksheet. If you use the *Active_data* worksheet, then the copy the information from section 2, "Copy data from crop data," and then copy rows 3 to 450 to section 3 (specified in cells G13:G16) and click the "Copy data to crop data" button. After calculating the required application depth for 0.05 leaching fraction, add the calculated fraction of baseline irrigation to the section 3 column in the G01 worksheet. Go to the Main worksheet. In cell G2, specify that three sections will be evaluated. After clicking Run, select position 3 in the Get Data combo box (upper right side of the worksheet). Find the "Water content" graph and the "Irrigation, rain depth, and leaching" graph with the Selection form. If rainfall appears in the graph, remove the rainfall from the *Active year weather* page for the first 100 days. Find the soil water salinity graph in the *Salinity* worksheet. Compare to the salinity levels in Example 26.4. Copy and paste the worksheets or graphs into this document. Use the graphs to assess the processes.
5. Calculate leaching fraction for irrigation water salinity 2 dS/m and required EC_e 1.5 dS/m?
6. What are the ratios EC_e/EC_{ave}, and EC_e/ EC_{dw} in Example 26.4? EC_{dw} is the leachate salinity. Discuss the importance of understanding these ratios with respect to crop management decisions?
7. Redo Example 26.5, but change the fertilizer application to 40 kg/ha on the first day application and change nitrate concentration in the irrigation water to 20 mg/L. Make a new hand calculation of the changes due to fertilizer application and irrigation during the first 3 days in the upper cell. Run the WINDS simulation for 100 days with the higher irrigation water nitrate concentration and higher fertilization rate on day 3. The irrigation rate will be the same as question 4. You can change the nitrogen data in the Active_data worksheet and copy it to section 3 in the *Crop_data* worksheet. Make sure that cell G5 in *Main* worksheet is marked True. Run the simulation from the *Main* worksheet. Select 3 in the *Get_data* combobox in the Main worksheet. Click the *View Nitrogen* data button. Copy the following graphs into your homework document: *Nitrate* (mg/kg) in layers, *Irrigation and drainage nitrate* (you might need to update both x and y axes from the selection form or from the axes), *Reactions*, and *Cumulative leaching, nitrate and reactions*. Assess the processes by looking at the graphs.
8. A soil has three 0.4 m layers, numbered 1, 2, and 3 from the bottom, with field capacity in all layers equal to 0.25. The initial water salinity in layers 1, 2, and 3 is, 23-, 7-, and 5-dS/m, respectively. ET is 10 mm/day with 20 %, 30 %, and 50 % of ET in layers 1, 2, and 3 respectively. Irrigation water salinity is 2 dS/m. The initial water content on the previous day in layers 1, 2, and 3 is 0.18, 0.15, and 0.10, respectively. Soil porosity is 0.4. An irrigation event adds 11 cm water to the soil in the morning. Compare to the final water content, actual salinity, and saturated paste extract salinity before the morning irrigation event. Compare the changes in water salinity and saturated paste extract salinity.
9. During a one day period, the upper layer of soil, 0.4 m depth, has a mineralization rate of 0.1 mg/L * m, a denitrification rate of 0.05 mg/L*m, and plant uptake of 1 kg/ha. One cm (average for the field) depth of water is added to the layer by drip irrigation and the irrigation water has a nitrate concentration of 20 mg/L. Transpiration removes 1.4 cm from the layer. No water leaches to the next layer. The initial water content is 0.18, and the initial nitrate concentration in the soil water is 15 mg/L. Calculate the final water content and nitrate concentration in the water. Calculate the kg/ha nitrate in the layer at the end of the day.