Soil Water Balance Module

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Soil Water Balance – why we need it?

- to assess the root zone soil water depletion/soil water content under different water regimes and soil, climatic and crop conditions;
- to design irrigation scheduling;
- to evaluate irrigation strategies;
- to estimate yield response to water and crop growth;
- to study the building of salt in the root zone under adverse irrigation conditions.
Soil Water Balance Components

Root zone depletion:

\[ D_{r,i} = D_{r,i-1} - P_i - IR_i - CR_i + ET_{c,i} + RO_i + DP_i \]

Soil moisture content:

\[ \Theta_{r,i} = \Theta_{r,i-1} + P_i + IR_i + CR_i - ET_{c,i} - RO_i - DP_i \]
Soil – Plant – Atmosphere Continuum

Atmosphere

Plant

Soil

CR (capillary rise) E – evaporation
IR T – transpiration
DP (deep percolation) P – precipitation
θ – Soil Moisture Content

θ_{FC} TAW
θ_{OYT}
θ_{PWP}
DYNAMIC SIMULATION MODEL

Time (t) – soil depth (z) – space grid

CR
(capillary rise)

E – evaporation
T – transpiration
P – precipitation
SMC – Soil Moisture Content
Soil Water Balance – common calculation scheme

\[ \theta_{ij} = \theta_{ij-1} + \Delta\theta_{i,dt} + \Delta\theta_{i,dt} + \Delta\theta_{i,dt} + \Delta\theta_{i,dt} \]

- \( \theta_{ij} \) - soil moisture content at depth \( z_i \) and at time level \( t_j \)

The greatest components of SWB in the Mediterranean
The opportunity to stored water in the soil root zone, or potential water storage ($W_{SP}$), depends on the actual water content in that zone ($W_{SA}$):

$$W_{SP} = W_{FC} - W_{SA}$$

For a rainfall event, the water infiltrated into the soil ($W_{inf}$) is given by:

$$W_{inf} = P - \text{Runoff}$$

Thus, water stored in the soil ($W_{ST}$) is obtained in the following way:

- If $W_{inf} \leq W_{SP}$, then $W_{ST} = W_{inf}$ and $DP = 0$
- If $W_{inf} > W_{SP}$, then $W_{ST} = W_{SP}$ and $DP = W_{inf} - W_{SP}$
Simplified Soil Water Balance for a rainfall event – an example of calculation

Assume:
- $P = 50 \text{ mm}$
- $W_{SA} = 20 \text{ mm}$
- $W_{FC} = 40 \text{ mm}$
- Runoff = 15 mm

Calculate water stored in the soil $W_{ST}$!

Calculation:
- Water infiltrated into the soil is $W_{inf} = P - \text{Runoff} = 50 - 15 = 35 \text{ mm}$
- Potential water storage is $W_{SP} = W_{FC} - W_{SA} = 40 - 20 = 20 \text{ mm}$
- Since $W_{inf} > W_{SP}$, then water stored in the soil is $W_{ST} = W_{SP} = 20 \text{ mm}$
- Deep percolation is $DP = W_{inf} - W_{ST} = 35 - 20 = 15 \text{ mm}$
Soil classification – from granulometric soil characteristics & soil triangle

Example:
Sand 60%
Clay 30%
Silt 10%

From the soil triangle this soil can be classified as Sandy Clay Loam
Soil hydraulic properties
- function of soil type

<table>
<thead>
<tr>
<th>SAT vol%</th>
<th>FC vol%</th>
<th>WP vol%</th>
<th>tau</th>
<th>Ksat mm/day</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>13</td>
<td>6</td>
<td>1.00</td>
<td>1500</td>
<td>Sand</td>
</tr>
<tr>
<td>38</td>
<td>16</td>
<td>8</td>
<td>0.95</td>
<td>800</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>41</td>
<td>22</td>
<td>10</td>
<td>0.75</td>
<td>500</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>46</td>
<td>31</td>
<td>15</td>
<td>0.60</td>
<td>250</td>
<td>Loam</td>
</tr>
<tr>
<td>46</td>
<td>33</td>
<td>13</td>
<td>0.50</td>
<td>150</td>
<td>Silt loam</td>
</tr>
<tr>
<td>43</td>
<td>33</td>
<td>9</td>
<td>0.35</td>
<td>50</td>
<td>Silt</td>
</tr>
<tr>
<td>47</td>
<td>32</td>
<td>20</td>
<td>0.45</td>
<td>125</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>50</td>
<td>39</td>
<td>23</td>
<td>0.40</td>
<td>70</td>
<td>Clay loam</td>
</tr>
<tr>
<td>52</td>
<td>43</td>
<td>27</td>
<td>0.30</td>
<td>20</td>
<td>Silty clay loam</td>
</tr>
<tr>
<td>50</td>
<td>39</td>
<td>27</td>
<td>0.42</td>
<td>75</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>54</td>
<td>50</td>
<td>32</td>
<td>0.20</td>
<td>15</td>
<td>Silty clay</td>
</tr>
<tr>
<td>55</td>
<td>54</td>
<td>39</td>
<td>0.10</td>
<td>2</td>
<td>Clay</td>
</tr>
</tbody>
</table>

The characteristics of the soil layer are the following hydraulic properties:

- **SAT**: soil water content [vol%] at saturation;
- **FC**: soil water content [vol%] at field capacity;
- **WP**: soil water content [vol%] at wilting point;
- **tau**: drainage characteristic (value between 1 and 0);
- **Ksat**: infiltration rate [mm/day] at saturation.
Soil Water Balance – common calculation scheme in crop growth models

\[ \theta_{ij} = \theta_{i,j-1} + \Delta \theta_{i,dt} + \Delta \theta_{i,dt} + \Delta \theta_{i,dt} + \Delta \theta_{i,dt} \]

\( \theta_{ij} \) - soil moisture content at depth \( z_i \) and at time level \( t_j \)
Drainage –
amount of water lost by free drainage as a function of time for any SWC between saturation and FC

\[
\frac{\Delta \theta_i}{\Delta t} = \tau (\theta_{sat} - \theta_{FC}) \frac{e^{\theta_i - \theta_{FC}} - 1}{e^{\theta_{sat} - \theta_{FC}} - 1}
\]

\(\Delta \theta_i/\Delta t\) : decrease in soil water content at depth \(i\), during time step \(\Delta t\) \([m^3 m^{-3} \text{day}^{-1}]\)
\(\tau\) : drainage characteristics, from 0 to 1, non-dimensional
\(\theta_i\) : actual soil water content at depth \(i\) \([m^3 m^{-3}]\)
\(\theta_{SAT}\) : soil water content at saturation \([m^3 m^{-3}]\)
\(\theta_{FC}\) : soil water content at field capacity \([m^3 m^{-3}]\)
\(\Delta t\) : time step

If \(\theta_i \leq \theta_{FC}\) then \(\Delta \theta_i/\Delta t = 0\)
If \(\theta_i = \theta_{SAT}\) then \(\Delta \theta_i/\Delta t = \tau(\theta_{SAT} - \theta_{FC})\)
Variation of soil water content in function of time in a free draining soil layer with a drainage characteristics of $\tau = 0.4$

$\tau$: drainage characteristics – expresses the decrease in soil water content of a soil layer, originally at saturation, at the end of the first day of free drainage.

$\tau = 0$: when soil layer is impermeable

$\tau = 1$: when complete drainage happens after one day
Soil Water Balance – common calculation scheme in crop growth models

\[ \theta_{ij} = \theta_{i,j-1} + \Delta \theta_{i,dt} + \Delta \theta_{i,dt} + \Delta \theta_{i,dt} \]

\( \theta_{ij} \) - soil moisture content at depth \( z_i \) and at time level \( t_j \)
**Infiltration**

- **Infiltration** refers to the downward flow of water from surface into the soil.

- **Percolation** refers to the movement of water through the soil profile.

**Indicative values of infiltration capacity [mm/hr] as a function of soil texture and vegetation cover**

<table>
<thead>
<tr>
<th>Texture</th>
<th>Vegetative soil</th>
<th>Bare soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loamy sand</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Loam</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Silt loam</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Clay loam</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

Source: Khonkeo, 1968
Runoff – basic considerations

- From the hydrological (engineering) point of view, the runoff from a drainage basin can be considered as a product (gain) in a hydrological cycle.

- Main climatic factors affecting runoff:
  - precipitation: form, duration, intensity, time and areal distribution, frequency of occurrence, antecedent precipitation, antecedent soil moisture, interception (vegetation species, composition, age, density of canopy, season of the year) ...

- Main physiographic factors affecting runoff:
  - basin characteristics: size, shape, slope, orientation, elevation, stream density
  - physical factors: land use and cover, soil type, infiltration conditions, permeability conditions, capacity of groundwater formations ...

- From the agronomic point of view, the runoff can be considered as precipitation losses in a rainfall-runoff analysis.
Runoff – SCS-USDA Curve Number (CN) method

- A **Curve Number** is an **empirical value** assigned to each watershed or portion of watershed based on:
  - Soil type;
  - Land use and treatment;
  - Antecedent moisture conditions (AMC).

- Antecedent moisture conditions are divided into:
  - AMC-I – soils are dry close to the wilting point, and satisfactory plowing or cultivation takes place;
  - AMC-II – average soil moisture conditions and management practices
  - AMC-III – the soil is nearly saturated – heavy rainfall or light rainfall and low temperatures occurred during the five days previous to the given storm.
# SCS-USDA method – CN values

<table>
<thead>
<tr>
<th>Description</th>
<th>Average % Impervious</th>
<th>Curve Number by Hydrologic Soil Group</th>
<th>Typical Land Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Residential (High Density)</td>
<td>65</td>
<td>77</td>
<td>85</td>
</tr>
<tr>
<td>Residential (Med. Density)</td>
<td>30</td>
<td>57</td>
<td>72</td>
</tr>
<tr>
<td>Residential (Low Density)</td>
<td>15</td>
<td>48</td>
<td>66</td>
</tr>
<tr>
<td>Commercial</td>
<td>85</td>
<td>89</td>
<td>92</td>
</tr>
<tr>
<td>Industrial</td>
<td>72</td>
<td>81</td>
<td>88</td>
</tr>
<tr>
<td>Disturbed/Transitional</td>
<td>5</td>
<td>76</td>
<td>85</td>
</tr>
<tr>
<td>Agricultural</td>
<td>5</td>
<td>67</td>
<td>77</td>
</tr>
<tr>
<td>Open Land – Good</td>
<td>5</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>Meadow</td>
<td>5</td>
<td>30</td>
<td>58</td>
</tr>
<tr>
<td>Woods (Thick Cover)</td>
<td>5</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>Woods (Thin Cover)</td>
<td>5</td>
<td>43</td>
<td>65</td>
</tr>
<tr>
<td>Impervious</td>
<td>95</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Water</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
SCS-USDA Curve Number (CN) method

Soil hydrological groups by means of infiltration rate

- **A** Soils having **high infiltration rates**, even when thoroughly wetted and consisting chiefly of deep, well to excessively-drained sands or gravels. These soils have a high rate of water transmission.

- **B** Soils having **moderate infiltration rates** when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

- **C** Soils having **slow infiltration rates** when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.

- **D** Soils having **very slow infiltration rates** when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay-pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.
SCS-USDA Curve Number (CN) method

Soil hydrological groups by means of potential runoff

A Lower Runoff Potential – Includes deep sands with very little silt and clay, also deep, rapidly permeable loess.

B Moderately Low Runoff Potential – Mostly sandy soils less deep than A, and less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting.

C Moderately High Runoff Potential – Comprises shallow soils and soils containing considerable clay and colloids, though less than that of group D. The group has below-average infiltration after thorough wetting.

D Highest Runoff Potential – Includes mostly clays of high swelling percentage, but the group also includes some shallow soils with nearly impermeable sub-horizons near the surface.
Runoff – SCS-USDA Curve Number (CN) method

Range of variation (**possible error?!**)

<table>
<thead>
<tr>
<th>AMC</th>
<th>Soil water content</th>
<th>CN value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Wilting point</td>
<td>45</td>
</tr>
<tr>
<td>II</td>
<td>Default value</td>
<td>65</td>
</tr>
<tr>
<td>III</td>
<td>Field capacity</td>
<td>84</td>
</tr>
</tbody>
</table>

\[
S = 254 \left( \frac{100}{CN} - 1 \right)
\]

\[
RO = \frac{(P - 0.2S)^2}{P + S - 0.2S}
\]

S: potential maximum storage (soil retention)

(0.2)*S: initial abstraction [mm] – the amount of water that can infiltrate before runoff occurs

CN: curve number

RO: amount of water lost by surface runoff [mm]

P: precipitation [mm]

**Initial abstraction 0.2S**

\[
CN45 \rightarrow 62 \text{ mm} \quad \text{Initially dry soil}
\]

\[
CN65 \rightarrow 27 \text{ mm} \quad \text{Initially moderately wet soil}
\]

\[
CN85 \rightarrow 9 \text{ mm} \quad \text{Soil is nearly saturated}
\]

Runoff starts when P>0.2S
Runoff – SCS-USDA Curve Number (CN) method

Example of calculation

Assume:

- P = 50 mm
- CN = 75 (agricultural land, moderate infiltration rate)

Calculate runoff and initial water abstraction in the soil!

\[ S = 254 \left( \frac{100}{CN} - 1 \right) = 84.7 \text{ mm} \quad \text{potential maximum storage} \]

Initial abstraction \( 0.2*S = 16.9 \text{ mm} \)

\[ RO = \frac{(P - 0.2S)^2}{P + S - 0.2S} = 9.2 \text{ mm} \quad \text{runoff} \]
Runoff – SCS-USDA Curve Number (CN) method

Range of variation as a function of AMC (possible error?!)
SCS USDA Curve number method – discussion

Wetness of the soil near the surface before precipitation

(e.g. Commercial - urban zone)
(e.g. Meadow area)
However, sometimes runoff can represent almost 100% of P even from agricultural fields.
Interception and Effective Rainfall Concept
Effective Rainfall ($P_{eff}$)

*a part of $P$ stored in the root zone and not lost by surface runoff or deep percolation*

(to be used over the total growing season, or on a monthly basis)

- **Fixed % of $P$**
  $$P_{eff} = P_{coeff} \times P$$

- **FAO/AGL Empirical Equation** for design purposes where 80% probability of exceedance is required
  - $P_{eff} = 0.6 \times P_{tot} - 10 \quad \text{for} \quad P_{tot} < 70\text{mm}$
  - $P_{eff} = 0.8 \times P_{tot} - 24 \quad \text{for} \quad P_{tot} > 70\text{mm}$

- **USDA Soil Conservation Method**
  - $P_{eff} = P_{tot}(125 - 0.2P_{tot}) / 125 \quad \text{for} \quad P_{tot} < 250\text{mm}$
  - $P_{eff} = 125 + 0.1P_{tot} \quad \text{for} \quad P_{tot} > 250\text{mm}$

Total rainfall is used (and not $P_{eff}$) in the water balance calculations for irrigation scheduling on a daily basis - the intake of rain into soil is determined and rainfall losses due to deep percolation and surface runoff are estimated according to actual soil moisture content in the root zone.
Interception and Effective Rainfall

27 January

2 March

17 March
Percentage of ground cover estimation in the field

27 January

2 March

17 March
Water extraction pattern throughout the root zone

**Uniform**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Water Extraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper 1/4</td>
<td>25 %</td>
</tr>
<tr>
<td>second 1/4</td>
<td>25 %</td>
</tr>
<tr>
<td>third 1/4</td>
<td>25 %</td>
</tr>
<tr>
<td>bottom 1/4</td>
<td>25 %</td>
</tr>
</tbody>
</table>

Typical water extraction pattern

**Non-uniform**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Water Extraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper 1/4</td>
<td>40 %</td>
</tr>
<tr>
<td>second 1/4</td>
<td>30 %</td>
</tr>
<tr>
<td>third 1/4</td>
<td>20 %</td>
</tr>
<tr>
<td>bottom 1/4</td>
<td>10 %</td>
</tr>
</tbody>
</table>
Soil layers and soil compartments

Source: Raes, 2002

Soil water content

Source: Raes, 2002
Soil Water Balance and Irrigation scheduling considerations

Knowing the soil water content (depletion) in the root zone we are able to decide the amount of water to supply. However, there are many other parameters to take into consideration...
# Field application efficiency of irrigation methods

<table>
<thead>
<tr>
<th>Irrigation method</th>
<th>APPLICATION PRACTICES</th>
<th>Field application efficiency in %</th>
<th>Average deep percolation as fraction of irrigation water applied to the field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler</td>
<td>Daytime application, moderately strong wind</td>
<td>60</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Nighttime application</td>
<td>70</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>0.25</td>
</tr>
<tr>
<td>Trickle</td>
<td></td>
<td>80-85</td>
<td>0.10-0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80-85</td>
<td>0.10-0.15</td>
</tr>
<tr>
<td>Basin</td>
<td>Poorly leveled and shaped</td>
<td>60</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Well leveled and shaped</td>
<td>75</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.3</td>
</tr>
<tr>
<td>Furrow</td>
<td>Poorly graded and sized</td>
<td>55</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>0.4</td>
</tr>
<tr>
<td>Border</td>
<td>Well graded and sized</td>
<td>65</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Source: FAO 38, 1980
Soil Water Retention

- Saturation
- Field capacity
- Wilting point

RAW - readily available water
TAW - total available water
Superfluous (free) water
Capillary water
Irrigation Scheduling Management Terms

- **TAW** - total available water
  - Water stored in the root zone between the field capacity and wilting point:
  \[
  TAW = 1000 \times (\theta_{FC} - \theta_{WP}) \times Rz
  \]
  - Where TAW is in mm, \( \theta_{FC} \) and \( \theta_{WP} \) are given in \( m^3 \ m^{-3} \), and the effective root depth \( Rz \) in \( m \)

- **RAW** - readily available depletion
  - A fraction (p) of TAW that can be extracted by crops without suffering water stress:
  \[
  RAW = p \times TAW
  \]
Root depth concept in irrigation scheduling

Root depth is affected by:
- soil texture, soil water management, and plant nutrient and oxygen availability

Effective root depth
- used in irrigation scheduling for estimates of TAW and RAW
- assumed to be less than maximum since 80-90% of plant’s feed roots are contained in the upper 60-75% of the root zone

\[
R_z = \begin{cases} 
R_{z,i} + \frac{D - D_p}{D_c - D_p} (R_{z,\text{max}} - R_{z,i}) & \text{if } D < D_c \\
R_{z,\text{max}} & \text{if } D = D_c \text{ or } D > D_c
\end{cases}
\]

- \( R_{z,i} \) - initial effective root depth at planting (4-10cm); \( R_{z,\text{max}} \) - maximum effective root depth; \( D \) - current calendar (Julian) day of the year; \( D_p \) - planting day; \( D_c \) - day of effective root cover
Management (Effective) Root Depth ($R_d$)

$R_d = R_{d,i} + \frac{D - D_p}{D_c - D_p} (R_{d,max} - R_{d,i})$

$R_d = R_{d,max}$

$R_{d,i}$ - initial effective root depth at planting (10-20cm); $R_{d,max}$ - maximum effective root depth; $D$ - current calendar (Julian) day of the year; $D_p$ - planting day; $D_c$ - day of effective root cover
Management (Effective) Root Depth Calculation

- Using the Kc values

\[ R_d = R_{d,i} + R_f \left( R_{d,max} - R_{d,i} \right) \]

- where \( R_f \) is the root factor \( 0 \leq R_f \leq 1 \)

\[ R_f = \frac{K_c - K_{c,ger}}{K_{c,max} - K_{c,ger}} \]

- \( K_c \) - crop coefficient for the growing stage under consideration
- \( K_{c,max} \) - maximum crop coefficient
- \( K_{c,ger} \) - crop coefficient for the germination stage
- \( R_{z,i} \) - initial effective root depth at planting 20 cm;
The readily allowable water depletion (RAW) is the percentage of available soil water which can be depleted between irrigations without serious water stress.

Values of RAW (as a percentage of TAW) are typically:
- 25-40% for high-value, shallow or sparsely rooted crops.
- 50% for deep-rooted crops.
- 60-65% for low-value, deep-rooted crops.
- May decrease by 5-10% when ETo > 6 mm/day.

FAO 33 recommended:
- 50% of TAW as an average “safe” level.
- Increase/decrease of 15% when ETo < 3 mm/day or ETo > 8 mm/day.
Range of root zone available water
that can be utilized before growth and/or yield is reduced

- decreasing root density
- increasing transpiration rate
- increasing root zone salinity
- increased water stress sensitivity
Allowable root zone water depletion

for various crops according to sensitivity to water stress

<table>
<thead>
<tr>
<th>Crop groups</th>
<th>Maximum evapotranspiration rate ETₘ [mm/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>0.80</td>
</tr>
<tr>
<td>4</td>
<td>0.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group</th>
<th>Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Onion, pepper, potato</td>
</tr>
<tr>
<td>2</td>
<td>Banana, cabbage, pea, tomato</td>
</tr>
<tr>
<td>3</td>
<td>Alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat</td>
</tr>
<tr>
<td>4</td>
<td>Cotton, sorghum, olive, grape, safflower, maize, soybean, sugarbeet, tobacco</td>
</tr>
</tbody>
</table>
Management allowable depletion (MAD)

- The percentage of available soil water which can be depleted between irrigations.
- MAD should be less than or equal to RAW except when deficit irrigation is applied.
- MAD may change during the season to account for sensitivity to water stress during critical developmental periods and for changes in rooting depth and evaporative demand.
  - Some crops require greater soil-water depletion directly before harvest to enhance the quality of fruit or grain.
- MAD may depend also on irrigation method, water delivery...
  - It is lower for drip than for sprinkler irrigation method.
Timing Irrigation Criteria

- **Allowable depletion of TAW (fraction)**
  - irrigation is applied whenever Dr drops below a predetermined fraction of TAW

- **Allowable depletion of RAW (fraction)**
  - irrigation is applied whenever Dr drops below a predetermined fraction of RAW

- **Allowable daily stress**
  - irrigation is applied whenever the actual ET rate drops below a predetermined fraction of potential ET rate

- **Allowable depletion amount**
  - irrigation is applied whenever a predetermined amount of water below field capacity is depleted
  - particularly useful in the case of high frequency irrigation systems (drip)

- **Fixed/variable calendar**
  - irrigation is applied 4 days, every week, etc. depending on growing stage
Depth Irrigation Criteria

- **Back to field capacity (+/-)**
  - the soil water content in the root zone is brought back to field capacity **plus or minus** a specified depth for salt leaching purposes or rainfall allowance respectively.

- **Fixed depth**
  - a predetermined amount of water is applied (adapted to specific irrigation method)
  - for high frequency irrigation there is no water stress risk but there is water excess risk (aeration problems)
Root zone water depletion (Dr) and irrigation water supply strategies

SOIL WATER CONTENT

- Field capacity
- Allowable depletion threshold
- Wilting point

Full Irrigation
Partial Irrigation
Deficit Irrigation

D_r=0
D_r<RAW
D_r>0
D_r=RAW
D_r>RAW

RAW
TAW
Fixed depth irrigation

SOIL WATER CONTENT

Field capacity

Irrigation

RAW

TAW

Allowable depletion threshold

Wilting point

time
Back to field capacity (+/-) irrigation

SOIL WATER CONTENT

Irrigation

Field capacity

TAW
Allowable depletion threshold

Wilting point

time

plus

minus

RAW

Back to field capacity (+/-) irrigation

SOIL WATER CONTENT

Irrigation

Field capacity

TAW
Allowable depletion threshold

Wilting point

time

plus

minus

RAW

Irrigation with leaching

- Field capacity (FC)
- Wilting point (WP)
- Irrigation = CWR + LR
- Allowable depletion threshold (TAW)
- Time
Root zone water depletion (Dr) and irrigation water supply strategies

\[ K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1 - p)TAW} \]
ETc adjusted for water stress:

\[
ET_{c,\text{adj}} = K_s K_c ET_o
\]

Diagram showing the relationship between \(\theta\) and \(K_s\), with a threshold for water stress indicated by a red line. The graph includes a parameter \(D_r\) representing depletion from the root zone.
Relative yield estimation for the whole growing season under water stress conditions

\[
1 - \frac{ET_{c,adj}}{ET_{c,max}}
\]

\[
(1 - \frac{Y_a}{Y_m}) = K_y (1 - \frac{ET_{c,adj}}{ET_{c,max}})
\]

Ya : actual yield;
Ym : maximum expected yield;
K_y : yield response factor (crop specific and varies during the growing season);
ET_{c,max} : ETc for optimal water supply
ET_{c,adj} : actual crop ET adjusted for water stress

K_y < 1
less sensitive

K_y = 1

K_y > 1
more sensitive

Source: Stewart et al., 1977
### Ky (yield response factor to water stress) values for some crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>$K_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>1.1</td>
</tr>
<tr>
<td>Beans</td>
<td>1.2-1.35</td>
</tr>
<tr>
<td>Cabbage</td>
<td>0.95</td>
</tr>
<tr>
<td>Citrus</td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.85</td>
</tr>
<tr>
<td>Grape</td>
<td>0.85</td>
</tr>
<tr>
<td>Maize</td>
<td>1.25</td>
</tr>
<tr>
<td>Onion</td>
<td>1.1</td>
</tr>
<tr>
<td>Peas</td>
<td>1.15</td>
</tr>
<tr>
<td>Pepper</td>
<td>1.1</td>
</tr>
<tr>
<td>Potato</td>
<td>1.1</td>
</tr>
<tr>
<td>Sorghum</td>
<td>0.9</td>
</tr>
<tr>
<td>Soybean</td>
<td>0.85</td>
</tr>
<tr>
<td>Spring Wheat</td>
<td>1.15</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>1.0</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>1.2</td>
</tr>
<tr>
<td>Sunflower</td>
<td>0.95</td>
</tr>
<tr>
<td>Tomato</td>
<td>1.05</td>
</tr>
<tr>
<td>Watermelon</td>
<td>1.1</td>
</tr>
<tr>
<td>Winter Wheat</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Source: FAO, 1998
Relative yield estimation for individual growth periods: a multiplicative approach

Multiplicative approach for \( N \) growing (sensitivity) stages:

\[
\frac{Y_a}{Y_m} = \prod_{i=1}^{N} \left[ 1 - K_{y,i} \left( 1 - \frac{ET_{c,adj,i}}{ET_{c,i}} \right) \right]
\]

Source: FAO 33, 1979; Rao et al., 1988
Deficit Irrigation Strategy: 
**minimizing** Yield reduction while **maximizing** ET reduction (water saving)

\[
\frac{Y_a}{Y_{max}}
\]

Relative water consumption (%)

Relative yield (%)

\(ET_{c,real}\)

\(ET_{c,max}\)
Example of RDI applied on a field crop during the phase tolerant to water stress
The effect of soil salinity on the $K_s$ and reduction of $ET_c$
Yield-salinity relationship and salinity-ET reduction relationship

Assumption:

\[ \frac{Y_a}{Y_m} = 1 - (EC_e - EC_{e,\text{thres}}) \frac{b}{100} \]

- \( Y_a \) - the actual crop yield,
- \( Y_m \) - the maximum crop yield expected when there is no salt stress,
- \( EC_e \) is the mean electrical conductivity of the saturation extract for the root zone,
- \( EC_{e,\text{thres}} \) - the threshold value of \( EC_e \) when yield reduction occurs;
- \( b \) is the factor of yield reduction (slope of the curve) in respect to increase of \( EC_e \) (\%/dS m\(^{-1}\))
**Salinity stress without water stress**

- EC_e > EC_e,threshold and Dr < RAW

- Salinity stress

\[
\frac{Y_a}{Y_m} = 1 - (EC_e - EC_{e,thres}) \frac{b}{100}
\]

- The reduction of yield

\[
(1 - \frac{Y_a}{Y_m}) = K_y (1 - \frac{ET_{c,adj}}{ET_{c,max}})
\]

- Reduction coefficient Ks

\[
1 - 1 + (EC_e - EC_{e,thres}) \frac{b}{100} = K_y (1 - K_s)
\]

\[
K_s = 1 - \frac{b}{K_y 100} (EC_e - EC_{e,thres})
\]
Water and salinity stress

- Water stress $Dr > RAW$

$$K_s = \frac{TAW - Dr}{TAW - RAW} = \frac{TAW - Dr}{(1 - p)TAW}$$

- Salinity stress $EC_e > EC_{e,threshold}$

$$K_s = 1 - \frac{b}{Ky \times 100} (EC_e - EC_{e,thres})$$

- Both, water ($Dr > RAW$) and salinity stress ($EC_e > EC_{e,threshold}$)

$$K_s = (1 - \frac{b}{Ky \times 100} (EC_e - EC_{e,thres})) \frac{TAW - Dr}{TAW - RAW}$$
Ks: Water stress and aeration stress (accounting for excess of water in the root zone)
Response of key processes to gradual development of water stress in the field

- Water stress intensity
- Restriction of canopy development
- Increase of growth of roots relative to shoots
- Osmotic adjustment
- Stomatal closure
- Leaf wilting and rolling
- Leaf senescence
- Leaf death by desiccation

Stress duration

Stress start

Time

Plant death

Source: adapted after Bradford and Hsiao, 1982
WATER STRESS THRESHOLDS – AquaCrop Approach

1 – Leaf expansion growth
2 – Stomatal closure
3 – Leaf (canopy) senescence

Ks (water stress factor)

FC

TAW

WP

RAW

threshold
AquaCrop approach:
Convex, linear and concave shapes for the water stress coefficient

If $f_{\text{shape}} < 0$ then $K_s$ function is concave

If $f_{\text{shape}} > 0$ then $K_s$ function is convex

$$K_s = 1 - \frac{e^{D_{\text{rel}} f_{\text{shape}}}}{e^{f_{\text{shape}}} - 1}$$
AQUACROP approach –
Water stress coefficient for leaf expansion growth

\[ P_{adj} = P_{lower} + C_a \left[ 0.04 \left( 5 - ET_{crop} \right) \right] \]

\( Ca \) – adjustment coefficient for \( ET_{crop} \neq 5 \text{mm/day} \)
AQUACROP approach – Water stress coefficient for canopy senescence

\[ P_{adj} = P_{upper} + C_a \left[ 0.04(5 - ET_{crop}) \right] \]

\( C_a \) – adjustment coefficient for \( ET_{crop} \neq 5 \text{ mm/day} \)
The effect of water stress on the reduction of root zone expansion for various shape factors \( f_{\text{shape}} \) and relative crop transpiration \( \frac{T_{\text{act}}}{T_{\text{pot}}} \).
Instead of conclusions

**Certain:**
- measured climatic variables
- measured average soil characteristics
- quality of irrigation water
- quantity of water applied and timing
- irrigation method (and its performances)
- some crop parameters (crop height, development stage, DAP, LAI, root depth...)

**Uncertain:**
- estimate of reference evapotranspiration and Kc values
- estimate of crop water requirements
- readily available water (total available water)
- crop water uptake pattern
- crop response function to deficit irrigation and/or excessive salt accumulation
- spatial and temporal variability