

Water limited yield

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Scope: questions/ challenges the tool addresses

This tool is designed for the following purposes:

- To estimate the effect on yields of climate and weather (deviations from average rainfall patterns such as drought; climate change)
- To estimate the effect on yields and water consumption of improved irrigation practices

The tool is intended for use at the field level. It allows for multiple cropping on the same land.

In essence, the tool implements the WEAP two-bucket soil moisture model. The upper bucket is represented by a loss term to the lower bucket or to interflow through percolation losses. Soil moisture in the lower bucket is not tracked. The tool also provides two new features not present in the WEAP soil moisture model:

1. The tool models crop yields under water-limited conditions. At present, WEAP does not calculate yields for the two-bucket soil-moisture model. The tool limits subsequent evapotranspiration from crops that at some stage are insufficiently watered.
2. Irrigation efficiency for different irrigation techniques is shown. The tool can portray the extent to which different irrigation practices actually succeed in increasing water availability to the plant. It can show, for example, to what extent drip irrigation replaces (unproductive) evaporation with (productive) transpiration. The WEAP soil moisture model does allow for different irrigation efficiencies through adjustments to upper and lower irrigation thresholds and crop coefficient values. The approach taken by this tool, however, provides a directly-interpretable parameter that reflects the efficiency of different irrigation technologies.

Target group

Model outputs are intended to be useful for planners. Model application requires a practitioner with experience in agriculture, and in the agricultural practices used in the watershed.

Requirements for tool application

The tool is a command-line program¹. Using it requires some facility with computers, including a degree of comfort with editing text files. The user must supply crop parameters, but many of these may be obtained from FAO, for example, parameter values for alfalfa, cotton,

¹ It can be downloaded from <http://www.kb-creative.net/sei/SRP/YieldModel/>, with sample files.

maize, wheat, vegetables, some fruits, sorghum, millet, and pasture. Additional parameters values are needed to specify soil characteristics, land cover, and cropping practices.

The following parameters and data are required to run the model:

- Climate data (daily)
 - Available irrigation depth (less than this might be used)
 - Precipitation depth
 - Reference evapotranspiration
- Crop parameters and data, by crop:
 - From FAO CropWat
 - Days for each growing stage
 - Crop coefficient K_c
 - Yield reduction coefficient K_y
 - Minimum and maximum leaf area indices
 - Root depth by stage
 - The maximum expected yield (this can be set to 1.0 to get a relative yield)
 - The starting date for each crop as an offset from either the start of a data file or the starting date of another crop
- Land and soil parameters
 - Conductivity
 - Maximum soil capacity (depth)
 - Saturation fraction
 - Fallow leaf area index
 - Fallow crop coefficient
 - Plant available water (PAW) coefficient, the ratio of the depth of water to the depth of wetted soil
 - A parameter for the runoff model used, either:
 - The runoff parameter for the WEAP soil water balance model
 - The shape parameter for the ARNO rainfall-runoff model
 - Irrigation parameters
 - Lower threshold for determining when to start irrigating
 - Upper threshold for determining when to stop irrigating

- An irrigation efficiency parameter expressing a bias towards transpiration over evaporation relative to natural precipitation for specific irrigation technologies

Note that by setting lower and upper irrigation thresholds to different values, irrigation efficiency is affected. All irrigation parameters affect overall efficiency of irrigation water use.

Description and application of the tool

The tool implements a one-dimensional soil moisture model, using it to determine if a crop is water-stressed. If it is, crop yields are reduced in subsequent time periods, and water requirements are adjusted in later time steps. The hydrological model is identical to that used in WEAP (Yates et al., 2005), aside from an additional irrigation efficiency parameter, as discussed below.

Basic Hydrological Model

The key equation is

$$S \frac{dz}{dt} = P_e(t) + I(t) - E(t) - r(t) - K_s z^2,$$

where S is total root zone storage (as a depth), $z(t)$ is the soil moisture expressed as a fraction of the total root zone storage, $P_e(t)$ is effective precipitation, $I(t)$ is irrigation, $E(t)$ is actual evapotranspiration, $r(t)$ is runoff, and K_s is the vertical hydraulic conductivity. Actual ET is given by

$$E(t) = E_0(t) K_c(t) \left(\frac{5z - 2z^2}{3} \right),$$

where $E_0(t)$ is reference ET and $K_c(t)$ is the crop coefficient.

The runoff term is (Yates et al., 2005; Yates, 1996)

$$r(t) = (P_e(t) + I(t)) z^F,$$

where F is the runoff resistance coefficient. At low values for F , nearly all water runs off, whereas at high F there is substantial runoff only when z is very close to one, and the ground is saturated. In the original formulation of Yates (1996), F is equal to the leaf-and-stem area index (LAI). The tool allows this as an option. Setting the value for this parameter to “LAI” will set F to the time-varying leaf area index.

Note that there is gradual loss of water from the root zone into a lower later or adjacent areas. This loss is represented by the term $-K_s z^2$.

Irrigation

The decision to irrigate or not is controlled by two parameters, the lower and upper irrigation fractions, f_{lower} and f_{upper} . Defined in terms of the root depth D and the plant available water (PAW) coefficient, ϕ , the conditions are

Condition to begin irrigation: $zS \leq f_{\text{lower}} \phi D$

Condition to end irrigation: $zS \geq f_{\text{upper}} \phi D$

Irrigation water application is calculated as

$$I = \min(I_{\text{max}}, f_{\text{upper}} \phi D - zS),$$

where I_{max} is the maximum available irrigation.

The upper and lower irrigation thresholds affect the irrigation efficiency for the field. In addition, in this tool there is an additional irrigation efficiency parameter that represents an improvement over the natural allocation between evaporation and transpiration, in order to capture the efficiency gains from technologies such as drip irrigation. Novák argued for the following model (see Novák and Havrila, 2005; Rockström, 2003)

$$T = ET_{\text{nat}} (1 - e^{-\beta\omega}),$$

where β is a coefficient approximately equal to 0.46 for a large number of canopies, T is transpiration, ET_{nat} is the “natural” evapotranspiration, and ω is the leaf area index. This equation partitions evaporation (E) and transpiration (T) using a simple factor. It is assumed that irrigation also partitions E and T, but using an adjusted factor,

$$T = ET_{\text{irr}} (1 - (1 - \varepsilon)e^{-\beta\omega}),$$

where ε is an efficiency. When $\varepsilon = 0$, then $T/ET_{\text{irr}} = T/ET_{\text{nat}}$, so that the partitioning between E and T is the same as for natural precipitation. When $\varepsilon = 1$, $T = ET_{\text{irr}}$, so that 100% of the water applied to the crop via irrigation is used directly by the crop. This can capture the benefits of, for example, microdrip irrigation systems, in which the water is delivered close enough to the root that there is very little evaporation. The transpiration required by the plant is the same for either irrigation or precipitation, so the reduction factor for the ET for irrigation water, f_{red} can be calculated by setting the two previous equations equal to each other,

$$f_{\text{red}} \equiv \frac{ET_{\text{irr}}}{ET_{\text{nat}}} = \frac{1 - e^{-\beta\omega}}{1 - (1 - \varepsilon)e^{-\beta\omega}}.$$

Yields

Yields are calculated using a modified version of the FAO CROPWAT model (Kassam and Smith, 2001). Yields in the FAO framework reach their maximum only if water is sufficient at each stage. For the model described in this note, what is desired is to estimate the yield given a particular pattern of water use, updating the calculated yield at the end of each stage. In contrast, in the FAO CROPWAT model, the yield is specified and, if it is below the maximum, the water use at each stage is assumed to be less than that of a crop that reaches its full yield, with the same reduction factor applied at each stage. Because the same reduction factor is applied at each stage in the FAO approach, for the dynamic model described in this note, yields are constrained by the most water-limiting previous stage. With this assumption, if the first stage is

the most water-limiting (or if no stage is water-limiting), then the end result will be identical to the CROPWAT calculation. If a later stage is more water-limiting, then water use will be higher than in the CROPWAT approach. Specifically, at each stage,

$$y' = \min \left\{ y, y_m \left[1 - K_y \left(1 - \frac{E_{\text{cum}}}{K_c E_{0,\text{cum}}} \right) \right] \right\}$$

where y is the yield at the end of the previous stage, y' is the yield at the end of the current stage, K_y is the yield coefficient, y_m is the maximum yield, E_{cum} is cumulative actual evapotranspiration over the stage, K_c is the crop coefficient during the stage, and $E_{0,\text{cum}}$ is cumulative reference evapotranspiration over the stage. If the yield falls below the maximum yield, then the crop coefficient is reduced, as in the FAO CROPWAT approach, so that in subsequent time steps the water requirements of the plant are lower than they would have been if the water supply had been sufficient.

Because water stress changes crop physiology and development, the approach taken to correct yields for water stress may not match outcomes in the field. The model has not yet been tested in an application. Furthermore, the model could be improved by using crop-specific factors to correct for evapotranspiration under water-stressed conditions (Kassam and Smith, 2001).

Application

A sample input file is shown below. Each input file describes a specific field, where multiple crops may be grown. Yields are updated over time by applying the FAO crop water method. An additional file supplies values for irrigation water, precipitation, and reference evapotranspiration over time. If at a particular growth stage there is insufficient water to maintain the full yield, then in subsequent growth stages less water is consumed by the crop.

```
# Define all crops, using FAO data
# Setting maxyield = 1.0 gives a relative yield compared to max
# Root depth is in meters
crop tomato -days {30 40 40 25} -kc {0.6 1.15 0.8} \
  -ky {0.4 1.1 0.8 0.4} -maxyield 1.0 -minlai 0.5 \
  -maxlai 4.0 -rootdepth {0.25 1.0}
crop soybean1 -days {15 15 40 15} -kc {0.5 1.15 0.5} \
  -ky {0.2 0.8 0.0 1.0} -maxyield 1.0 -minlai 0.5 \
  -maxlai 4.0 -rootdepth {0.3 1.0}
crop soybean2 -days {15 15 40 15} -kc {0.5 1.15 0.5} \
  -ky {0.2 0.8 0.0 1.0} -maxyield 1.0 -minlai 0.5 \
  -maxlai 4.0 -rootdepth {0.3 1.0}

# Say when each crop will start (first show above ground), relative to
# the start of the data file
start tomato 320
start soybean1 0
start soybean2 10+tomato ;# This means "10 days after the tomato growing period"
```

```

# Initialize values for the land
# conductivity: Vertical hydraulic conductivity
# maxsoilcap: Maximum soil water capacity
# satfrac: Initial soil moisture, as fraction of max capacity
# fallowLAI: The leaf area index on fallow land
# fallowKc: The crop coefficient for fallow land
# plantavailwater: PAW coefficient, the ratio of water depth to wetted soil depth
# runoffresistance: The WEAP runoff resistance factor
  land -conductivity 6.0 -maxsoilcap 200.0 \
  -satfrac 0.5 -fallowLAI 0.1 -fallowKc 0.1 \
  -runoffresistance 3 -plantavailwater 0.15

# Irrigation parameters
# efficiency: Efficiency of delivering water for T rather than E to the crop
# lowerthreshold: When soil moisture gets below this threshold, start irrigating
# upperthreshold: when soil moisture is above this threshold, stop irrigating
irrigation -efficiency 0.80 -lowerthreshold 0.5 \
  -upperthreshold 0.8

# Get data from file. Data are in the order:
# irrigation, ET0, Precip
# Specify order here using I E P
getdata "sampledata.dat" I E P

```

Partial output from running this file is shown below. In the input file, the maximum yield was given as “1.0”, so yields are relative to the maximum yield. Until the end of the run, yield can be thought of as a “potential yield,” which begins at the maximum and either stays the same or declines after each growth stage, depending on the availability of water.

Day	Irrigation Depth	tomato Yield	soybean1 Yield	soybean2 Yield	Root Zone Storage (frac.)
1	0.0000	1.0000	1.0000	1.0000	0.5540
2	0.0000	1.0000	1.0000	1.0000	0.7087
3	0.0000	1.0000	1.0000	1.0000	0.7270
4	0.0000	1.0000	1.0000	1.0000	0.6986
5	0.0000	1.0000	1.0000	1.0000	0.7112
6	0.0000	1.0000	1.0000	1.0000	0.6858
7	0.0000	1.0000	1.0000	1.0000	0.7092
8	0.0000	1.0000	1.0000	1.0000	0.6927
726	0.0000	0.7565	0.7644	0.6897	0.8916
727	0.0000	0.7565	0.7644	0.6897	0.8962
728	0.0000	0.7565	0.7644	0.6897	0.8883
729	0.0000	0.7565	0.7644	0.6897	0.8709
730	0.0000	0.7565	0.7644	0.6897	0.8727

The file tracks yields of crops at each stage. At the end of the file the final yield of each crop is reported. For this file, maximum yields were all set at 1.0, so that the reported yields are relative to the maximum. In this case there was insufficient water, and yields of tomato and soybean (in two different seasons) are 76%, 76%, and 69% of their maximum potential. Root zone storage at the end of the run is at 87% of the maximum root depth.

As can be seen, yield values should only be read off at the end of the file, although the intermediate yield values provide information about when water stress limited the growth of the plant. Meanwhile, root zone storage can be taken from across the entire run.

Lessons learnt and recommendations

The yield model is still in development and has not yet been applied to the watershed. Although this model can be run before any major modeling is carried out, it is more useful to use it after running a hydrological and water-allocation model such as WEAP. In this way, the water allocation can be calculated, and the hydrological parameters can be calibrated.

Limitations

The tool has not been tested in an actual application. Until then, it is recommended that outputs be treated skeptically and that the tool not be used in isolation. One potential concern regarding the model is that if a crop is water-stressed during one growth cycle, then the response of the crop to water in subsequent growth stages will be different than if water had been sufficient. This is because water stress affects the timing of flowering, plant maturity, and other factors (Kassam and Smith, 2001). The way that yield reductions are transferred from one growth stage to the next in this model may therefore be unrealistic, and need to be checked in application. Also, the model could be improved by adding crop-specific corrections to evapotranspiration under water-stressed conditions (Kassam and Smith, 2001). This has not yet been done.

References

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Contacts and links

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