wabal
(wb1, wb2, wb3)

rené gommes
rene.gommes@jrc.ec.europa.eu
Ver. 20100816 (ver.0)

1. Introduction

wabal (**wa**ter **bal**ance) is a linux/windows command-line implementation on the standard FAO water balance as currently computed in AgroMetShell (FAO), GWSIViewer (JRC), CMBox[1] (FAO and EC) and some other tools. It is proposed here in three "flavours" (**wb1, wb2, wb3**) that differ only in the way in which inputs and outputs are handled.

The simple algorithm was first introduced by Frère and Popov (1979, 1986) as a tool to monitor cereals in the (semi-arid) Sahel at the regional scale. Various modifications were added over the years to enable the approach to be used in humid areas and on other crops as well. It is a very widely tested tool in and outside FAO (Verdin and Klaver, 2002; Rojas et al., 2005; Fischer et al., 2006) and is available, as mentioned, under various names and implementations.

Wabal produces a number of variables/indicators that are used in crop monitoring and forecasting. One of them is the Water Satisfaction Index (**WSI**), which many people use as their main crop monitoring variable[2]. **WSI** measures the extent to which crop water requirements have been met. For instance, **WSI**=100% indicates no water stress; values close to 50% are usually associated with severely water stressed crop from which no yield is expected.

2. The Crop Specific Soil Water Balance[3] (CSSWB)

The CSSWB is the standard implementation of the Frère and Popov algorithm. It is a coarse regional model[4] that describes the water relations of a soil-plant-atmosphere system and puts out the variables (indicators, predictors) that will be used to estimate yields. Typical output variables include actual crop evapotranspiration (ETA) over certain crop growth phases (such as flowering), excess or deficit water, the above mentioned Water Satisfaction Index, and others.

The main reason why a water balance provides value-added variables that are related with crop yields derives from the direct link between the water balance and the energy balance of crops. Plants absorb solar energy for their photosynthesis: the radiant energy (light) is

1 See http://www.fao.org/NR/climpag/pub/cm_box_4.pdf for an overview and additional links.

2 In spite of some shortcomings, e.g. the fact that it is a standardised variable unrelated to production potential, of the fact that yield=f(WSI) reaches a plateau before yields attain their maximum value.

3 Section largely borrowed from Gommes et al., 2009)

4 Regional (district, province...) as opposed to local (field scale)

converted to chemical energy but also to heat which, in turn, is used to evaporate water.

Although the mechanism is more complex (Gommes, 1998, 1999), there is a practically direct and linear relation between the amount of water (evapo)transpired and the amount of phosynthetates, provided water stress is not too severe, as has been known since the early work by the Wageningen school (De Wit et al., 1978) and innumerable studies since then. The linear relation holds across several orders of magnitude of spatial scales (from leaf to plant to field to region) and provides the theoretical basis why most quantitative crop modelling resorts to evapotranspiration as the main crop simulation variable.

The CSSWB[5] is made "crop specific" through the use of crop specific coefficients (crop coefficients) which relate crop water demand to atmospheric evapotranspiration potential, cycle lengths and planting dates.

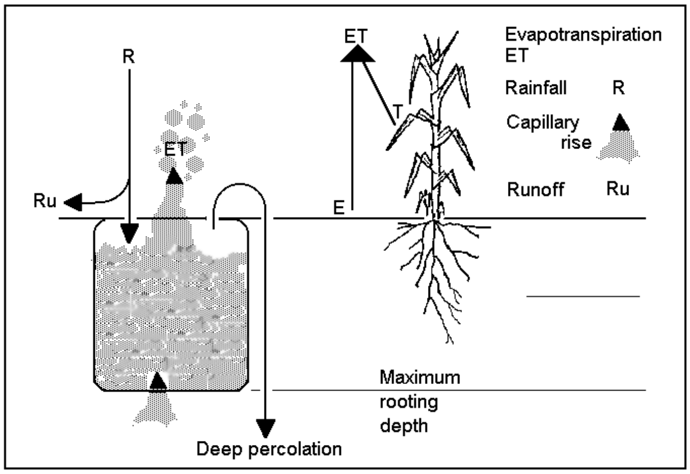

Figure 1: Schematic representation of a crop specific soil water balance. R: rainfall; Ru: run-off; E: soil water evaporation; T: plant water transpiration; ET: evapotranspiration, the sum of E and T. All variables are expressed in litres of water per m2 per day or dekad (10-day period), or mm. Capillary rise of water from deeper layers was not taken into account. Illustration simplified from Gommes, 1999.

The CSSWB is typically computed for point locations (typically meteorological stations, or equally spaced gridpoints) at dekadal[6] time steps. Calculations start up to 10 dekads before planting (“pre-season period) in order to ensure that realistic soil moisture values are used at the time of planting, a most critical variable in crop forecasting.

At the end of each time step, soil moisture results from soil moisture at the beginning of the period plus water supply (rainfall and/or irrigation) less crop water requirements[7] (fig. 1). Soil is mainly characterised by a water holding capacity (WHC[8]). Water supply that exceeds WHC is lost through deep percolation and run-off.

Crop water need and use are normally computed based on one of the numerous available formulae for Potential Evapotranspiration, but mostly using the standard equations proposed by Penman and subsequently modified by Monteith (Allen et al., 1998). The calculation of PET requires five meteorological variables: maximum temperature Tx, minimum temperature Tn, air humidity, wind speed and solar radiation. Unfortunately, the five variables are not always available, so that simplified method are often resorted too (e.g. Hargreaves, based only on extreme temperatures Tx and Tn).

5 A complete description is provided by Gommes, 1999.

6 A dekad is a ten-day period used in operational agrometeorology. The term derives from a WMO recommendation to distinguish dekads from decades. The dekad numbering starts in January (1-10 January, dekad 1) until December (21-31 December, dekad 36).

7 Provided sufficient water is available. If availability is less than requirement, crops undergo a stress.

8 The amount of water stored between the top layer and the maximum depth reached by the roots.

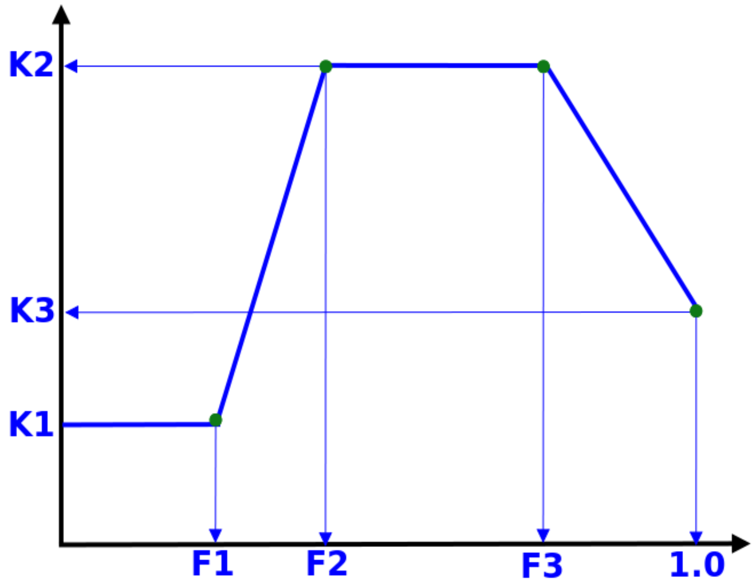

Figure 2: definition of crop coefficients based on six parameters. Kcr conventionally subdvides the crop cycle into 4 phenological phases: 1, initial; 2, vegetative; 3 flowering and 4, maturation.

Actual crop water requirements depend on PET as well as crop stage and are is estimated, for each dekad of the crop cycle, by multiplying PET by the above-mentioned crop coefficient which depends on crop type and crop stage (phenology). This also assumes that crop phenology is known (especially planting dates and cycle lengths). Crop coefficients are usually defined using six coefficients as illustrated in fig. 2.

3. Format of command line

`wb1`, **`wb2`** and **`wb3`** adopt different command line formats, although most parameters are identical. For all of them, the number of data items (either provided on the command line or in files) can be variable depending on the parameters themselves. For instance, the water balance covers a certain number of "pre-season" dekads (symbolised by **`Prs_dek`**) as well as the dekads that make up the crop cycle length (symbolised by **`Cyc_dek`**). The total number of rainfall and PET items required is thus the sum of **`Cyc_dek + Prs_dek`**. The maximum number of dekads allowed (**`Max_dek = Cyc_dek + Prs_dek`**) is set to 50 for **`wb1`** and **`wb2`** and to 70 for **`wb3`**.

`wb1` reads parameters from the command line, but weather variables (rainfall, PET and optionally irrigation water amounts – all in mm) and crop coefficients are taken from files; detailed results are output to files or to the console. Consistency and error checks are done on the parameters; **`wb2`** reads all inputs (parameters plus weather variables) from the command line, and does the same level of checks as **`wb1`**. **`wb3`** is a fast production version of **`wabal`**: it takes all inputs from the command line, carries out no checks on the data and writes only summary outputs to the console, where they can be intercepted by any other programme and used as input for further processing. Both **`wb1`** and **`wb2`** will intercept data or input errors, display an message and then halt. wb3 will not diagnose any errors. The philosophy is that testing is to be done with **`wb1`** and **`wb2`**, but "production" with **`wb3`**.

4. Definition of input parameters

Not all parameters are used for all the versions of **wabal**. Details specific to **wb1**, **wb2** and **wb3** are given below.

Cyc_dek: crop cycle length in dekads

Prs_dek: number of pre-season dekads, i.e. the number of dekads before planting over which a soil water balance is computed

Prs_Kcr: pre-season crop coefficient, i.e. a fictitious crop coefficient that is applied to the fields before the crops are actually planted. This value is normally close to K1 (see below)

WHC_mm: soil water holding capacity, i.e. the amount of water in litres/m² (= mm) that the crop stores in the rooting zone and that is easily available

Bund_mm: the height of the bund (mm) that surrounds the fields (as in irrigated or lowland rice) and that traps water over the soil

Stress_thresh: a number between 0 and 1 that expresses from which fraction of WHC the crop starts experiencing a water stress. For instance, with **Stress_thresh** set to 0.3 and **WHC_mm** = 100, the crop being monitored is assumed to suffer a water stress if soil moisture drops below 30 mm. The **Stress_thresh** is used to compute crop water stress for different phenological phases.

Ri and Xi: two "atavistic" and very empirical variables that continue to be in demand. **Ri** is the amount (%) by which the water satisfaction index is reduced in the event excess rainfall exceeds **Xi**. For instance, assume a crop is not water stressed, and the **WSI** is 100%. with **Ri**=3% and **Xi**= 80 mm, the **WSI** drops from 100% to 97% when water excess reaches 80 mm per dekad.

F1, F2, F3, K1, K2, K3: the parameters defining the crop coefficient as well as the phenological phases (see fig. 2).

wb1

wb1 takes input from the command line and from files **RAIN.DAT, PET.DAT, IRRIG.DAT** and **KCR.DAT**[9]

The **wb1** parameters also include the following:

n/y/a: a switch to indicate the modality of irrigation. **n** denotes no irrigation, i.e. a rainfed crop. **y** specifies planned or farmer supplied irrigation, for which the amounts must be specified; with **a** (automatic irrigation), water is supplied automatically by the programme whenever there is a water stress, i.e. ever time soil moisture drops below the stress threshold. In that case, water is supplied up to the stress threshold (**Stress_threshold*WHC**, mm)

v/s/f: specifies the type of output. **v** prints out verbosely detail of calculations to **OUT.TXT**,

[9] Linux users: note the names are spelled with capitals.

while **s** directs them to the console (screen). With **f**, the summary outputs goes to file **OUT.CSV**.

path - with final / (or \ for windows users) specifies the complete path where input and output files are read/written, i.e. the path of files **RAIN.DAT, PET.DAT, IRRIG.DAT, KCR.DAT, OUT.TXT and OUT.CSV**.

Command line syntax:

wb1 Cyc_dek Prs_dek Prs_Kcr WHC_mm Bund_mm Stress_thresh Ri Xi n/y/a v/s/f path

Example

wb1 20 5 0.22 100 100 0.80 3 90 n f /home/ergosum/myfiles/programs/freebasic/projects/wb1/

wb2 and **wb3**

wb2 and **wb3** take all inputs from the command line; as indicated, **wb3** does no check whatsoever on inputs, except for the empty command line, which generates a messages and halts the programme.

The syntax is slightly different for **wb2** and **wb3 (wb3** does not require the **v/s** switch as all output is to the console)

wb2 Cyc_dek Prs_dek Prs_Kcr WHC_mm Bund_mm Stress_thresh Ri Xi n/y/a v/s F1 F2 F3 K1 K2 K3 rainfall_values PET_values [irrigation_values]

wb3 Cyc_dek Prs_dek Prs_Kcr WHC_mm Bund_mm Stress_thresh Ri Xi n/y/a F1 F2 F3 K1 K2 K3 rainfall_values PET_values [irrigation_values]

4. Output samples (all with wb2)

4.1 Pure rainfed crop

wb2 10 5 0.5 100 50 0.25 5 50 n v 0.2 0.5 0.8 0.5 1 0.5 21 22 231 24 25 10 11 12 13 14 15 161 171 18 19 23 22 21 120 19 18 17 16 151 141 131 12 11 10 9

writes the following output to **OUT.TXT**

```
Run of 08-17-2010 at 10:47:22

Cycle length in dekads                                        10
# of preseason wabal dekads                                   5
Pre-season Kcr                                                0.5
Water holding capacity in mm                                  100
Bund height in mm                                             50
Deficit threshold (0-1)                                       0.25
Excess water (Xi, mm) above which WSI_correction is applied   50
WSI_correction (%) when Excess>Xi (0 for no correction)       5
Irrigation ? Yes or No or Automatic I/N/A                     N

    Dek  phase  KCr    rain   Irrig   ETP    WatReq  Soilwat TwatReq   Def    Exc   ETA    Rix  AutIrr
    1    0    0.500    21.0     0.0    23.0   11.5      9.5
```

```
  2   0   0.500    22.0     0.0    22.0   11.0     20.5
  3   0   0.500   231.0     0.0    21.0   10.5    150.0
  4   0   0.500    24.0     0.0   120.0   60.0    114.0
  5   0   0.500    25.0     0.0    19.0    9.5    129.5
  6   1   0.500    10.0     0.0    18.0    9.0    130.5      9.0    0.0    0.0    9.0   0.0   0.0
  7   1   0.500    11.0     0.0    17.0    8.5    133.0     17.5    0.0    0.0    8.5   0.0   0.0
  8   2   0.667    12.0     0.0    16.0   10.7    134.3     28.2    0.0    0.0   10.7   0.0   0.0
  9   2   0.833    13.0     0.0   151.0  125.8     21.5    154.0    3.5    0.0  125.8   0.0   0.0
 10   2   1.000    14.0     0.0   141.0  141.0      0.0    295.0  130.5    0.0   35.5   0.0   0.0
 11   3   1.000    15.0     0.0   131.0  131.0      0.0    426.0  141.0    0.0   15.0   0.0   0.0
 12   3   1.000   161.0     0.0    12.0   12.0    149.0    438.0    0.0    0.0   12.0   0.0   0.0
 13   3   1.000   171.0     0.0    11.0   11.0    150.0    449.0    0.0  159.0   11.0   5.0   0.0
 14   4   0.750    18.0     0.0    10.0    7.5    150.0    456.5    0.0   10.5    7.5   5.0   0.0
 15   4   0.500    19.0     0.0     9.0    4.5    150.0    461.0    0.0   14.5    4.5   5.0   0.0

  Total ETA               239.50
          by phase            17.50
          by phase           172.00
          by phase            38.00
          by phase            12.00
  Total Surplus           184.00
          by phase             0.00
          by phase             0.00
          by phase           159.00
          by phase            25.00
  Total Deficit           275.00
          by phase             0.00
          by phase           134.00
          by phase           141.00
          by phase             0.00
  Total water requirement   461.00
  WSI (raw)                51.95
  WSI (corr. for surplus)    46.95
```

If **s** is specified instead of **v**:

wb2 10 5 0.5 100 50 0.25 5 50 n s 0.2 0.5 0.8 0.5 1 0.5 21 22 231 24 25 10 11 12 13 14 15 161 171 18 19 23 22 21 120 19 18 17 16 151 141 131 12 11 10 9

the output to the console is

239.5 17.5 172 38 12 183.9 0 0 159 24.9 274.9 0 133.9 141 0 461 52 47

i.e. the 18 summary outputs from **OUT.TXT**:

```
Total ETA over crop cycle: 239.50 mm
ETA for phase 1 (initial): 17.50 mm
ETA for phase 2 (vegetative): 172.00 mm
ETA for phase 3 (flowering): 38.00 mm
ETA for phase 4 (maturation): 12.00 mm
Total water surplus over crop cycle: 184.00 mm
Excess water for phase 1: 0.00 mm
Excess water for phase 2: 0.00 mm
Excess water for phase 3: 159.00 mm
Excess water for phase 4: 25.00 mm
Total water deficit over crop cycle: 275.00 mm
Total water deficit for phase 1: 0.00 mm
Total water deficit for phase 2: 134.00 mm
Total water deficit for phase 3: 141.00 mm
Total water deficit for phase 4: 0.00 mm
Total water requirements: 461.00 mm
WSI without empirical excess correction: 51.95 %
WSI with empirical excess correction: 46.95 %
```

4.2 Automatic irrigation

wb2 10 5 0.5 100 50 0.25 5 50 a v 0.2 0.5 0.8 0.5 1 0.5 21 22 231 24 25 10 11 12 13 14 15 161 171 18 19 23 22 21 120 19 18 17 16 151 141 131 12 11 10 9

writes the following output to **OUT.TXT**

Run of 08-17-2010 at 11:05:04

Cycle length in dekads	10
# of preseason wabal dekads	5
Pre-season Kcr	0.5
Water holding capacity in mm	100
Bund height in mm	50
Deficit threshold (0-1)	0.25
Excess water (Xi, mm) above which WSI_correction is applied	50
WSI_correction (%) when Excess>Xi (0 for no correction)	5
Irrigation ? Yes or No or Automatic I/N/A	A

Dek	phase	KCr	rain	Irrig	ETP	WatReq	Soilwat	TwatReq	Def	Exc	ETA	Rix	AutIrr
1	0	0.500	21.0	0.0	23.0	11.5	9.5						
2	0	0.500	22.0	0.0	22.0	11.0	20.5						
3	0	0.500	231.0	0.0	21.0	10.5	150.0						
4	0	0.500	24.0	0.0	120.0	60.0	114.0						
5	0	0.500	25.0	0.0	19.0	9.5	129.5						
6	1	0.500	10.0	0.0	18.0	9.0	130.5	9.0	0.0	0.0	9.0	0.0	0.0
7	1	0.500	11.0	0.0	17.0	8.5	133.0	17.5	0.0	0.0	8.5	0.0	0.0
8	2	0.667	12.0	0.0	16.0	10.7	134.3	28.2	0.0	0.0	10.7	0.0	0.0
9	2	0.833	13.0	0.0	151.0	125.8	25.0	154.0	3.5	0.0	125.8	0.0	3.5
10	2	1.000	14.0	0.0	141.0	141.0	25.0	295.0	127.0	0.0	39.0	0.0	127.0
11	3	1.000	15.0	0.0	131.0	131.0	25.0	426.0	116.0	0.0	40.0	0.0	116.0
12	3	1.000	161.0	0.0	12.0	12.0	150.0	438.0	0.0	24.0	12.0	0.0	0.0
13	3	1.000	171.0	0.0	11.0	11.0	150.0	449.0	0.0	160.0	11.0	5.0	0.0
14	4	0.750	18.0	0.0	10.0	7.5	150.0	456.5	0.0	10.5	7.5	5.0	0.0
15	4	0.500	19.0	0.0	9.0	4.5	150.0	461.0	0.0	14.5	4.5	5.0	0.0

Total ETA	268.00	
by phase		17.50
by phase		175.50
by phase		63.00
by phase		12.00
Total Surplus	209.00	
by phase		0.00
by phase		0.00
by phase		184.00
by phase		25.00
Total Deficit	246.50	
by phase		0.00
by phase		130.50
by phase		116.00
by phase		0.00
Total water requirement	461.00	
WSI (raw)	100.00	
WSI (corr. for surplus)	95.00	

4.3 Planned irrigation of 100 mm/dekad at 5 dekad intervals

wb2 10 5 0.5 100 50 0.25 5 50 i v 0.2 0.5 0.8 0.5 1 0.5 21 22 231 24 25 10 11 12 13 14 15 161 171 18 19 23 22 21 120 19 18 17 16 151 141 131 12 11 10 9 100 0 0 0 0 100 0 0 0 0 100 0 0 0 0

writes the following output to **OUT.TXT**

Run of 08-17-2010 at 11:11:59

Cycle length in dekads	10
# of preseason wabal dekads	5
Pre-season Kcr	0.5
Water holding capacity in mm	100
Bund height in mm	50

```
Deficit threshold (0-1)                                    0.25
Excess water (Xi, mm) above which WSI_correction is applied   50
WSI_correction (%) when Excess>Xi (0 for no correction)     5
Irrigation ? Yes or No or Automatic I/N/A                  I
```

Dek	phase	KCr	rain	Irrig	ETP	WatReq	Soilwat	TwatReq	Def	Exc	ETA	Rix	AutIrr
1	0	0.500	21.0	100.0	23.0	11.5	109.5						
2	0	0.500	22.0	0.0	22.0	11.0	120.5						
3	0	0.500	231.0	0.0	21.0	10.5	150.0						
4	0	0.500	24.0	0.0	120.0	60.0	114.0						
5	0	0.500	25.0	0.0	19.0	9.5	129.5						
6	1	0.500	10.0	100.0	18.0	9.0	150.0	9.0	0.0	80.5	9.0	5.0	0.0
7	1	0.500	11.0	0.0	17.0	8.5	150.0	17.5	0.0	2.5	8.5	5.0	0.0
8	2	0.667	12.0	0.0	16.0	10.7	150.0	28.2	0.0	1.3	10.7	5.0	0.0
9	2	0.833	13.0	0.0	151.0	125.8	37.2	154.0	0.0	0.0	125.8	5.0	0.0
10	2	1.000	14.0	0.0	141.0	141.0	0.0	295.0	114.8	0.0	51.2	5.0	0.0
11	3	1.000	15.0	100.0	131.0	131.0	0.0	426.0	41.0	0.0	115.0	5.0	0.0
12	3	1.000	161.0	0.0	12.0	12.0	149.0	438.0	0.0	0.0	12.0	5.0	0.0
13	3	1.000	171.0	0.0	11.0	11.0	150.0	449.0	0.0	159.0	11.0	10.0	0.0
14	4	0.750	18.0	0.0	10.0	7.5	150.0	456.5	0.0	10.5	7.5	10.0	0.0
15	4	0.500	19.0	0.0	9.0	4.5	150.0	461.0	0.0	14.5	4.5	10.0	0.0

```
Total ETA                  355.17
          by phase            17.50
          by phase           187.67
          by phase           138.00
          by phase            12.00
Total Surplus              268.33
          by phase            83.00
          by phase             1.33
          by phase           159.00
          by phase            25.00
Total Deficit              155.83
          by phase             0.00
          by phase           114.83
          by phase            41.00
          by phase             0.00
Total water requirement    461.00
WSI (raw)                   77.04
WSI (corr. for surplus)     67.04
```

```
WatSup=WatSoil+Rain+Irrigation
WatBal=WatSup-WatReq
SELECT CASE WatBal
   CASE is >WHCB
      WExc=WatBal-WHCB
      WatSoil=WHCB
      WDef=0
   CASE WHC to WHCB
      WatSoil=WatBal
      WDef=0
      WExc=0
   CASE WHCstress to WHC
      WatSoil=WatBal
      WDef=0
      WExc=0
   CASE 0 to WHCstress
      WatSoil=WatBal
      WDef=WHCstress-WatBal
      WExc=0
   CASE is <0
      WatSoil=0
      Wdef=WHCstress-WatBal
      WExc=0
END SELECT

Eta=WatSup
IF WatSup>WatReq then Eta=WatREq

AutIrrig=0
IF AutIrrigOn and WatBal<WHCstress THEN
   AutIrrig=WDef
   Watsoil=WHCstress
end if
```

Figure 3: core of the water balance programme with determination of water surplus (WExc) and deficit (Wdef). WatSup stands for water supply, WatReq for water requirement (crop coefficient * PET), Watsoil for soil moisture. WHC, WHCB (soil WHC + bund height, both in mm), WHCStress and 0 are values the water balance (WatBal) is compared against.

5. Required files

As indicated, input files are required only for **`wb1`**. Note that output files are overwritten at every run of the programmes.

6. Overall methodology

The core of the algorithms is illustrated in fig. 3 and 4.

Fig. 3 contains a portion of the programme illustrating how the water balance (water supply – water requirements) is compared with various threshold values illustrated in fig. 4. The code is sufficiently clear and should not require any explanation.

The portion of the programme is run for every dekad of the crop cycle.

7. Software implementation

`wabal` was programmed using FreeBasic (http://www.freebasic.net) version 0.21.0 Beta (released 20100722) in a linux (Ubuntu 10.04) environment. It was compiled under Linux and Windows XP running on a VirtualBox V.3.1.8. The windows version was subsequently tested as well under Windows 6.1.7600.

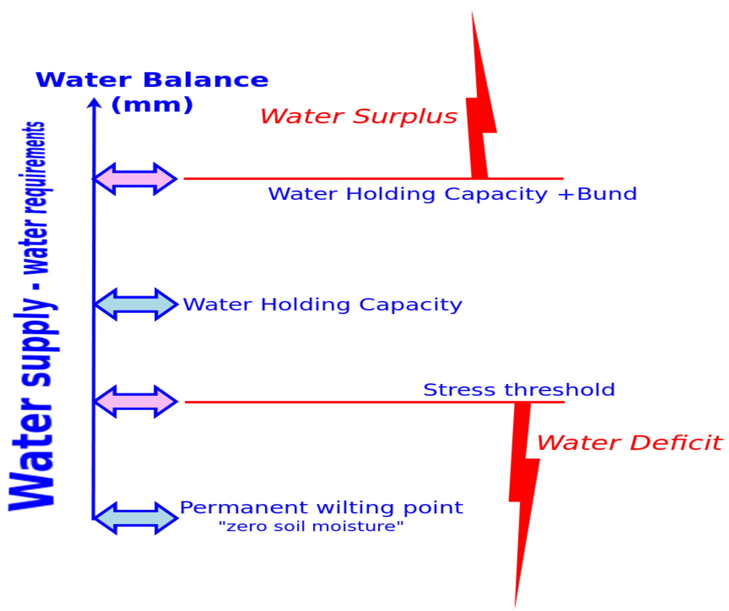

Figure 4: thresholds against which the water balance is compared to determine surplus, deficit and ETA

8. References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements, FAO Irrigation and drainage paper 56. FAO, Rome, Italy, 300 pp. (http://www.fao.org/docrep/X0490E/x0490e00.HTM)

de Wit, C.T., J. Goudriaan, H.H. van Laar, F.W.T. Penning de Vries, R. Rabbinge, H. van Keulen, W. Louwerse, L. Sibma & C. de Jonge, 1978. Simulation of assimilation, respiration and transpiration of crops. Pudoc, Wageningen, 141 pp.

Fischer, G., F.N. Tubiello, H. van Velthuizen & D.A. Wiberg, 2007. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990-2080. Technological Forecasting & Social Change, 74(7):1083-1107.

Frère, M. and G.F. Popov. 1979. Agrometeorological crop monitoring and Forecasting. FAO Plant Production and Protection Paper No 17. FAO, Rome. 64 pp.

Frère, M. and G.F. Popov. 1986. Early Agrometeorological crop yield forecasting. FAO Plant Production and Protection Paper No 73. FAO, Rome. 150 pp.

Gommes, R., 1998. Agrometeorological crop yield forecasting methods. Proc. Internat.Conf. on Agricultural Statistics, Washington 18-20 March 1998. Edited by T.Holland and M.P.R. Van den Broecke. International statistical Institute, Voorburg, The Netherlands. Pp 133-141.

Gommes, R., 1999. Roving Seminar on crop-yield weather modelling; lecture notes and exercises. WMO. Geneva, 153 pp. (The document can be downloaded from ftp://extftp.fao.org/SD/Reserved/Agromet/Documents/agro003a.pdf. (A related document in French is also available: ftp://ext ftp.fao.org/SD/Reserved/Agromet/Documents/TD_prevrec.PDF)

Gommes, R., T. El Hairech, D. Rosillon, R. Balaghi and H. Kanamaru, 2009. Impact of Climate Change on agricultural yields in Morocco. World Bank-Morocco study on the impact of climate change on the agricultural sector. 105 pp. Downloadable from ftp://ext-ftp.fao.org/SD/Reserved/Agromet/WB_FAO_morocco_CC_yield_impact/report/

Rojas, O., F. Rembold, A. Royer and T. Negre, 2005. Real-time agrometeorological crop yield monitoring in Eastern Africa. Agronomie, Vol. 25, No.1, 63-77.

Verdin, J. and Klaver, R. (2002). Grid cell based crop water accounting for the famine early warning system. Hydrological Processes, 16: 1617-1630.