WATEM_C version 1.0 Manual

1.Introduction

WATEM_C model is a spatially distributed model integrating soil erosion and SOC (soil organic carbon) cycling. The soil redistribution by water erosion is based on the WATEM model (Van Oost et al., 2000) . The water erosion component of WATEM_C uses an adapted version of the Revised Universal Soil Loss Equation (RUSLE) to calculate mean annual soil loss values. Runoff patterns are calculated with a flow algorithm that takes into account field borders and road infrastructures. Sediment is routed along these flow paths to the nearest river using a transport capacity term that is proportional to the potential rill erosion rate. WATEM_C, however, does not predict sediment transport within a river, bank erosion or floodplain sediment deposition. It focuses on the prediction of water erosion and sediment delivery to rivers. The SOC cycling component of WATEM_C is based on the three-pool C model (namely active (A), slow (S) and passive (P) C pools) by Wang et al. (2015). All the three C isotopes (^{12}C, ^{13}C and ^{14}C) are included in our model, and thus there are 9 isotope- C pool classes (i.e. ^{12}A, ^{13}A, ^{14}A, ^{12}S, ^{13}S, ^{14}S, ^{12}P, ^{13}P, and ^{14}P) considered in this model. A discrimination ratio is used to denote the difference in the mineralization rate between isotopes. C input and C mineralization rate is scaled to soil depth using an exponential equation. The model uses flexible time step and vertical resolution of the soil profile so that it can be applied in various settings to avoid the problem of calculation time.

WATEM_C can be used to:

- estimate soil loss and sediment deposition rates and patterns by water erosion
- display vertical distribution of ^{137}Cs and SOC caused by advection and diffusion, and soil truncation and burial by erosion
- display spatial variability of ^{137}Cs, SOC stock, δ^{13}C and Δ^{14}C values due to soil erosion

This manual provides end-users all possible information necessary to apply WATEM_C for case studies. More information about the scientific background and applicability can be found in the following publications. Use of this program is free. However, if any use of the programs included is made in publications, reference should be made to the following papers with respect to this work:

- Van Oost K, Govers G, & Desmet PJJ, 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecology 15 (6), 579-591.
- Van Rompaey A, Verstraeten G, Van Oost K, Govers G & Poesen J, 2001. Modelling mean annual sediment yield using a distributed approach. Earth Surface Processes and Landforms 26 (11), 1221-1236.

- Verstraeten G, Van Oost K, Van Rompaey A, Poesen J & Govers G, 2002. Evaluating an integrated approach to catchment management to reduce soil loss and sediment pollution through modelling. Soil Use and Management, 18, 386-394.
- Wang, Z., Doetterl, S., Vanclooster, M., van Wesemael, B., and Van Oost, K, 2015. Constraining a coupled erosion and soil organic carbon model using hillslope-scale patterns of carbon stocks and pool composition, Journal of Geophysical Research: Biogeosciences, 2014JG002768, 10.1002/2014JG002768.

2. Installation

Two versions of codes are prepared for WATEM_C. One version is used at the soil profile scale programmed in MATLAB, while the other one is used at the landscape scale programmed in Pascal. The MATLAB codes can be edited and run in MATLAB of recent version such as MATLAB R2018b. The Pascal codes can be edited in compilers of recent versions such as Lazarus IDE v2.0.0. The compiled executable file (WATME_C.exe) can be run in program such as R of recent version such as R version 3.5.3.

3. Run the soil profile version in MATLAB

An example of run the soil profile version (reference_scenario.m) is presented in the code files. The users should first assign values of relevant parameters (see Table 1 for the names and descriptions of these variables), and then run the three main C cycling processes: 'C_initialization', 'C_equilibrium', 'carbon'. The model initialized the C profiles as well as its C pool and isotopic compositions based on the values of C inputs, C decomposition rate, first-order kinetics, humification coefficient and initial C isotopic compositions. Then, the model run for a period for the C profile to reach equilibrium condition. After that, the model can be run in various scenarios as defined by the users through modifying relevant parameter values. In the soil profile version, processes of soil erosion are not presented, and soil redistribution rate was treated as a parameter whose value can be assigned by the users.

4. Run the landscape scale version in R

The default values of the parameters are given in the codes programmed in Pascal, but the model gives the users a chance to modify most of the parameter values when the executable file (WATEM_C.exe) is called in other programming language such as R. In order to call the executable file in R, it is necessary to prepare the GIS-layers, and the custom values of the parameters if the user does not want to run the model in default parameter values. When calling the executable file, the filenames of the raster files and custom values of parameters should be clarified after the names of these variables. The names of these variables should be kept the same as the names in the Pascal codes, and they cannot be changed (see Table 1 for the names and descriptions of these variables). The model initialized the C profiles as well as its C pool and isotopic compositions based on the values of C inputs, C decomposition rate and initial C isotopic composition. Then, the model run for a period for the C profile to reach equilibrium

condition. After that, the model can be run in various scenarios as defined by the users through modifying relevant parameter values.

Below is an example of calling the executable file in R:

Step1: Prepare raster file
In order to call the executable file in R, it is necessary to prepare the GIS-layers first.

```
###### LAND USE
parcel_fileName <- "PARCEL.tif"
PARCEL <- raster(paste(input_dir,parcel_fileName,sep='/'))
writeRaster(PARCEL, filename =paste0(work_dir,'/LAND_USE.RST'),
            format ='IDRISI',NAflag =0, datatype ="INT2S",overwrite =TRUE)

######## C Factor
Cfactor_fileName <- "C_factor.tif"
C <- raster(paste(input_dir,Cfactor_fileName,sep='/'))
writeRaster(C, filename = paste0(work_dir,'/C_factor.RST'),
            format = "IDRISI",NAflag = 0,datatype = "FLT4S",overwrite = TRUE)
```

Step 2: Set parameter values
The default values of the parameters are given in the codes programmed in Pascal, but the model gives the users a chance to modify the parameter values when the executable file (WATEM_C.exe) is called in other programming language such as R. In this case, the custom values of the parameters should be assigned in R before running the executable file. Various model scenarios can be defined by setting the parameter values.

```
### close erosion by setting start year and end year
### close diffusion and advection by setting K0 and v0


erosion_start_year <- 2100
erosion_end_year <- 2100

## variables for C cycling
depth_interval <- 5
depth <- 100

tillage_depth <- 5

deltaC13_ini_top <- -27.0
deltaC13_ini_bot <- -27.5
deltaC14_ini_top <- 50.0
deltaC14_ini_bot <- -500.0
```

Step 3: Run the model

When calling the executable file, the filenames of the raster files and custom values of parameters should be clarified after the names of these variables. The names of these variables should be kept the same as the names in the Pascal codes, and they cannot be changed (see Table 1 for the names and descriptions of these variables). The model initialized the C profiles as well as its C pools and isotopic compositions based on the values of C inputs, C decomposition rate, first-order kinetics, humification coefficient and initial C isotopic compositions. Then, the model run for a period for the C profile to reach equilibrium condition. After that, the model can be run in various scenarios.

```
cmd <- paste0("WATEM_C.exe -dir ",work_dir,
    " -o ","output",
    " -d ","DEM.rst",
    " -p ","LAND_USE.rst",
    " -u ","RKP.rst",
    " -c ","C_factor.rst",
    " -k ","KTC.rst",
    " -MC_f 1 -t 100 -r mf -b 1400 -ktil 0 -pdep 25 -frac 0 -w 1 -w_d_exp 0",
    " -C_input ", toString(format(C_input,nsmall=3)),
    " -C_input2 ", toString(format(C_input2,nsmall=3)),
    " -depth ", toString(depth),
    " -depth_interval ",toString(depth_interval),
    " -tillage_depth ",toString(tillage_depth),
    " -time_equilibrium ", toString(time_equilibrium),
    " -erosion_start_year ", toString(erosion_start_year),
    " -erosion_end_year ",toString(erosion_end_year),
    " -k1 ",toString(format(k1,nsmall=3)),
    " -k2 ",toString(format(k2,nsmall=3)),
    " -k3 ",toString(format(temp_data,nsmall=3)),
    " -hAS ",toString(format(hAS,nsmall=3)),
    " -hAP ",toString(format(hAP,nsmall=3)),
    " -hSP ",toString(format(hSP,nsmall=3)),
    " -r_exp ",toString(format(r_exp,nsmall=3)),
    " -i_exp ",toString(format(i_exp,nsmall=3)),
    " -a_erer ",toString(format(a_erer,nsmall=3)),
    " -b_erero ",toString(format(b_erero,nsmall=3)),
    " -K0 ",toString(format(K0,nsmall=3)),
    " -Kfzp ",toString(format(Kfzp,nsmall=3)),
    " -v0 ",toString(format(v0,nsmall=3)),
    " -vfzp ",toString(format(vfzp,nsmall=3)),
    " -time_step ",toString(time_step),
    " -c14input ","C14input.txt",
    " -c13input ","C13input.txt",
    " -Cs137input ","Cs137_input.txt")

# run command
system(cmd)
```

5. Model input

 WATEM_C requires the input of various constants as well as several GIS-layers. This model uses Idrisi32 raster data (developed at Clark Labs, MA, USA). It is important that all GIS-layers cover exactly the same area, that the resolutions are equal, and thus also that the dimensions (i.e. number of rows and columns) are identical. The user must also take care that the area covered by the GIS-layers is larger than the study area (e.g. a catchment).

5.1. DEM

WATEM_C needs a Digital Elevation Model (DEM) of the study area in order to calculate slope gradients and contributing areas. Since the erosion component of the model is based on topography, model results are strongly affected by the quality of the DEM. The height values and resolution of the DEM must have the same units! It is also very important that the DEM has no pits, i.e. closed depressions, which are due to interpolation errors, as it will result in major errors when computing flow patterns and contributing areas.

5.2. Parcel

This map is in fact a reclassified land use map that makes a distinction between arable land, forest, pasture, road infrastructure and build-up areas, and rivers. Each of these land use categories has a different identifier.

5.3. Soil erodibility (K-factor)

This map displays the soil erodibility factor of the RUSLE (K-factor) expressed in $kg\ m^{-2}\ h\ MJ^{-1}\ mm^{-1}$. Soil erodibility can be calculated from the RUSLE nomograph or using empirical equations to predict the K-factor from the geometric mean particle diameter and organic matter content.

5.4. Crop erosivity (C-factor)

This map displays the crop erosivity factor of the RUSLE (C-factor) which is a dimensionless parameter ranging from 0 (indicating no erosion is taking place under this crop) to 1 (i.e. the erosion compared to fallow conditions).

5.5. Rainfall erosivity (R-factor)

The RUSLE rainfall erosivity parameter (R-factor) need to be given in $MJ\ mm\ m^{-2}\ h^{-1}$. One can only supply one value for R as it is assumed that R is uniform for the whole study area, which is typically in the order of a few km² only. For larger areas, spatial variability in rainfall erosivity may be more important.

5.6. Erosion control efforts (P factor)

This factor adjusts the effect of erosion control measurements such as terraces and management practices.

5.7. Transport capability coefficient (Ktc)

This map displays the spatial variability of the transport capability within the catchment. Its unit is m.

5.8. Other input

In order to capture the temporal variability of ^{137}Cs fallout and input of ^{13}C and ^{14}C, model input on the ^{137}Cs fallout rate and ^{13}C and ^{14}C input are prepared in 3 text files. In these 3 text files, the first line contains one number, and it denotes the number of years simulated in the model. The following lines contain two numbers with the first number

denoting the year and the second number denoting the value of ^{137}Cs fallout, ^{13}C or ^{14}C input. The unit of ^{137}Cs fallout is Bq m^{-2} yr^{-1}, and the unit for ^{13}C and ^{14}C input is ‰.

6. Model output

WATEM_C model generates various results on erosion and SOC as listed below. They are stored in the folder "output".

- Spatial distribution of sediment production and deposition within the catchment
- Sediment export from the catchment
- Spatial variability of ^{137}Cs activities of each soil layer
- Spatial distribution of the nine C isotope- C pool classes (i.e. ^{12}A, ^{13}A, ^{14}A, ^{12}S, ^{13}S, ^{14}S, ^{12}P, ^{13}P, and ^{14}P) of each soil layer. Spatial distribution of C stock and δ^{13}C and Δ^{14}C values of required soil layers can be calculated based on above C isotope- C pool data.

Table 1. Description of variable names and their default values

Parameter	Description	Unit	Default values
erosion_start_year	the year erosion starts	yr	2000
erosion_end_year	the year erosion ends	yr	2050
depth_interval	depth of soil layer in the model	cm	5
depth	soil depth considered	cm	150
tillage_depth	depth of plow layer for cropland	cm	25
deltaC13_ini_top	δ^{13}C value of top soil layer in the initialized soil profile	‰	-27
deltaC13_ini_bot	δ^{13}C value of bottom soil layer in the initialized soil profile	‰	-25
deltaC14_ini_top	Δ^{14}C value of top soil layer in the initialized soil profile	‰	50
deltaC14_ini_bot	Δ^{14}C value of bottom soil layer in the initialized soil profile	‰	-500
time_equilibrium	time for the spin run of model to get the C profile reach equilibrium condition	yr	1000
deltaC13_input_default	δ^{13}C value of C input in the spin run period	‰	-30
deltaC14_input_default	Δ^{14}C value of C input in the spin run period	‰	100
Sand_ini_top	Sand fraction of top soil layer in the initialized soil profile	%	15
Silt_ini_top	Silt fraction of top soil layer in the initialized soil profile	%	70
Clay_ini_top	Clay fraction of top soil layer in the initialized soil profile	%	15
Sand_ini_bot	Sand fraction of bottom soil layer in the initialized soil profile	%	15

Silt_ini_bot	Silt fraction of bottom soil layer in the initialized soil profile	%	70
Clay_ini_bot	Clay fraction of bottom soil layer in the initialized soil profile	%	15
K0	diffusion term of the top soil layer (Eq. 20)	m yr^{-1}	0.5
Kfzp	detph-attenuation of diffusion (Eq. 20)	m^{-1}	0.15
v0	advection term of the top soil layer (Eq. 19)	m yr^{-1}	0.2
vfzp	detph-attenuation of advection (Eq. 19)	m^{-1}	0.15
time_step	the length of period for the model to iterate	yr^{-1}	5
a_erer	coefficient on the enrichment of SOC in mobilized soil (a in Eq. 5)	-	1
b_erero	coefficient on the enrichment of SOC in mobilized soil (b in Eq. 5)	-	2000
b_erdepo	coefficient on the enrichment of SOC in deposited sediment (d in Eq. 5)	-	4000
k1	turnover rates of the active ^{12}C pool	yr^{-1}	2.1
k2	turnover rates of the active ^{13}C pool	yr^{-1}	0.03
k3	turnover rates of the active ^{14}C pool	yr^{-1}	0.005
hAS	humification coefficients from the active pool to the slow pool	-	0.12
hAP	humification coefficients from the active pool to the passive pool	-	0.02
hSP	humification coefficients from the slow pool to the passive pool	-	0.02
r0	the r parameter at the top soil layer	-	1
C_input	C input from root	Mg C ha^{-1} yr^{-1}	0.7
C_input2	C input from leaf litter	Mg C ha^{-1} yr^{-1}	0.5
r_exp	exponential decreasing coefficient of r with depth	m^{-1}	3.30
i_exp	exponential decreasing coefficient for the root C input with depth	m^{-1}	6
R$_{disc\_13}$	discrimination ratio between ^{13}C and ^{12}C	-	0.9985
R$_{disc\_14}$	discrimination ratio between ^{14}C and ^{12}C	-	0.9985