9.8 Dynamic calculation of plant development

Phenology is of growing importance for hydrological water balance simulations, especially in the context of impact studies on climate change. Recent studies have shown that phenological phases (i.e. start and length) can significantly change under changing climate conditions. In addition, phenology can also show pronounced year-to-year variations, mainly depending on the seasonal course of air temperature.

Until now plant development was statically simulated by using predefined intra-annual courses of vegetation dynamics. Since WaSiM-ETH 7.8.x this deficiency is remedied. Now temperature-induced variations in the timing of phenological phases can be dynamically calculated. For this purpose, WaSiM-ETH offers three different phenological models which can only be used if time series of air temperature are available. The applicability of the models is not limited to daily model time steps but also possible in any other time steps. The necessary conversion from non-daily temperature values into daily values is performed internally by WaSiM-ETH.

Table 10: Comparison of phenological models implemented into WaSIM-ETH

Model name in WaSiM-ETH	DynamicPhenology_1 (DP1)	DynamicPhenology_2 (DP2)	DynamicPhenology_3 (DP3)
Model type	„Thermal Time Model“	„Sequential Model“	„Thermal Time Model“
Start of growing period	dynamically simulated	dynamically simulated	dynamically simulated
Next stages of growing	predefined (relatively to the start day)	predefined (relatively to the start day)	dynamically simulated
Landuse type to simulate	trees, groves	trees, groves	grasses, arable crops

9.8.1 DynamicPhenology_1 (DP1)

DP1 represents a simply “themal time model” and simulates the phenological response of trees to changes in air temperature. The model does not take dormancy into account. It assumes that the release of dormancy is usually reached at the end of the year. Leaf unfolding only starts when plant-specific heat sums (forcing units) have been reached. The “forcing units” are calculated after the logistic function of Sarvas (1974):

$$S_f(t) = \sum_{i=t_1}^{t} R_f(T_i) \qquad S_f(t_2) := F^* \tag{9.8.1}$$

$$R_f(T_i) = 0 \qquad \text{for} \quad T_i \le T_{Bf} \tag{9.8.2}$$

$$R_f(T_i) = \frac{28.4}{1 + \exp\left(-0.185 \cdot \left(T_i - T_{Bf} - 18.4\right)\right)} \qquad \text{for} \quad T_i > T_{Bf} \tag{9.8.3}$$

with
- S_f — state of forcing
- R_f — forcing rates
- F^* — forcing units; heat sum which has to be reached before the phenophase can be started
- T_i — daily mean temperature [°C]
- T_{Bf} — plant-specific base temperature for „forcing“ [°C]
- t_1 — end of dormancy; start day for calculating F* [JulDays]
- t_2 — start of the phenophase (active growth) [JulDays]

From Equations 9.8.1 - 9.8.3 it can be seen that DP1 only requires the optimization of three parameters: F^*, t_1 and T_{Bf} (in the WaSiM-ETH control file these parameters have slightly different names: F^*, *DP1_t1_dorm*, *DP1_T_Bf*).

The DP1 model can be activated by setting the plant-specific method identifier in the primary [landuse_table] to “DynamicPhenology_1“. This table entry signalizes WaSiM-ETH that phenology has to be calculated dynamically and that DP1 parameters have to be read in.

Besides the three above-mentioned parameters WaSiM-ETH needs two additional parameter entries in its [landuse_table]:

- *JDReset_TStart* [JulDays]:
  guaranteed a proper start of a new vegetation period (reset from *TStart* to -1 and reset of the „forcing units“ to zero)
- *maxStartJDforDP1* [JulDays]:
  denotes the last possible starting day for the use of DP1 within the actual calendar year. In the case that the model is started after this date, *TStart* is set automatically to:

  $$TStart = maxStartJDforDP1 - delta \quad \textbf{(9.8.4)}$$

  Here *TStart* denotes the start of the phenophase (active growth) and has to be set to -1 in the parameter row *JulDays*. During the initialization the model looks for this value and stores the column number for *TStart*. The value in the following column is interpreted as delta [JulDays]. It denotes the end of leaf unfolding.

  It is worthy to note that the entries for *JulDays* before and after these both days (*TStart* and *delta*) are fixed (resp. variable with the altitude only) and used as always (cf. method “VariableDayCount”). That means that the course of the phenological development after its (dynamically calculated) start follows the well-known old model scheme and uses statically predefined vegetation curves. For these predefined sections it is possible to consider the influence of altitude on plant development whereas this feature can not be used for the column entries *TStart* and *delta*. In this case the parameter *AltDep* (altitude dependence) has to be set to zero because here the air temperature is already implicitely considered. Furthermore it is not possible to interpolate between parameters which are earlier than *TStart*.

SARVAS, R. (1974): Investigations on the annual cycle of development of forest trees II. Autumn dormancy and winter dormancy. Communicationes Instituti Forestalis Fenniae, 84 (1), 1-101.

9.8.2 DynamicPhenology_2 (DP2)

DP2 is a „sequential model“ for simulating the timing of phenology for trees and groves. In contrast to DP1 it considers both the dormancy and the following phase of ontogenetic development.

Normally trees require a certain period with chilling temperatures before they can react to higher temperatures, which force the development of buds and induce leaf unfolding and lowering in spring (Chmielewski et al., 2005). That means that the release of dormancy is only possible if the “chilling units” are reached. The DP2 “chilling-forcing” model calculates the plant-specific heat and chilling units as follows:

$$S_c(t) = \sum_{i=t_0}^{t} R_c(T_i) \quad \text{with} \quad S_c(t_1) := C^* \quad \textbf{(9.8.5)}$$

$$S_f(t) = \sum_{i=t_1}^{t} R_f(T_i) \quad \text{with} \quad S_f(t_2) := F^* \quad \text{and} \quad F^* = a \cdot e^{b \cdot C^*} \quad \textbf{(9.8.6)}$$

$$R_c(T_i) = 0 \qquad \text{for } T_i \le z_1 \text{ or } T_i \ge z_2 \qquad \textbf{(9.8.7)}$$

$$R_c(T_i) = \frac{T_i - z_1}{T_{Bc} - z_1} \qquad \text{for } z_1 < T_i \le T_{Bc} \qquad \textbf{(9.8.8)}$$

$$R_c(T_i) = \frac{T_i - z_2}{T_{Bc} - z_2} \qquad \text{for } T_{Bc} < T_i < z_2 \qquad \textbf{(9.8.9)}$$

$$R_f(T_i) = 0 \qquad \text{for } T_i \le T_{Bf} \qquad \textbf{(9.8.10)}$$

$$R_f(T_i) = \frac{28.4}{1 + \exp\left(-0.185 \cdot \left(T_i - T_{Bf} - 18.4\right)\right)} \qquad \text{for } T_i > T_{Bf} \qquad \textbf{(9.8.11)}$$

with	S_c	state of chilling
	R_c	chilling rates
	C^*	chilling units; chilling sum which has to be reached before the dormancy can be finished
	S_f	state of forcing
	R_f	forcing rates
	F^*	forcing units; heat sum which has to be reached before the phenophase can be started
	a, b	empirical parameter
	T_i	daily mean temperature [°C]
	T_{Bc}	plant-specific base temperature for „chilling" [°C]
	T_{Bf}	plant-specific base temperature for „forcing" [°C]
	z_1	constant (for forest = -3.4 and for fruit trees = 3.0)
	z_2	constant (for forest = 10.4 and for fruit trees = 12.0)
	t_o	start of dormancy; start for calculating C* [JulDays]
	t_1	end of dormancy; start for calculating F* [JulDays]
	t_2	start of the phenophase (active growth) [JulDays]

Similar to DP1 the phenological model DP2 has to be activated by setting a plant-specific method identifier in the primary [landuse_table]. In the case of DP2 the table entry is "DynamicPhenology_2".

For using DP2 WaSiM-ETH requires the following plant-specific parameter entries (for explanations see above):

```
# extract from the primary landuse table

[landuse_table]
1
5 oak  {method = DynamicPhenology_2;
RootDistr        = 1.0;
TReduWet         = 0.95;
LimitReduWet     = 0.5;
HReduDry         = 3.45;
IntercepCap      = 0.35;
StressFactorDynPhen = 1.0;
F*               = 221.2;
DP1_t1_dorm      = 1;
DP1_T_Bf         = 0;
DP2_t0_dorm      = 244;
DP2_t1_dorm      = 60;
DP2_T_Bf         = 0.2;
DP2_T_Bc         = 8.4;
DP2_Par_a        = 231.6;
DP2_Par_b        = 0.0;
DP2_Offset_1     = -3.4;
DP2_Offset_2     = 10.4;
JDReset_TStart   = 1;
maxStartJDforDP1 = 150;
JulDays          =  1    -1      +10     258     288     319     349;
#(max) JulDays    =  1    130     200     217     293     319     366;
#ForcingThreshold = -1    334.8   1024.3  -1      1143.3  -1      -1;
...
```

Note that DP2 cannot be used for simulating the phenology of the first model year because at this time WaSiM-ETH does not know the state of chilling (S_c). In this case WaSiM-ETH changes automatically the phenological model from DP2 to DP1. This switsch setting can only deactivated if results from previous model runs are available for the initialization of DP2.

CHMIELEWSKI, F.-M., MÜLLER, A., KÜCHLER, W. (2007): Possible impacts of climate change on natural vegetation in Saxony (Germany). Int J Biometeorol, 50: 96-104.

9.8.3 DynamicPhenology_3 (DP3)

The third implemented phenological model is DP3. It is a simple "thermal time model" focusing mainly on the simulation of phenophases for crops. DP3 calculates the forcing rates (R_f) very simplified as growing-degree-days (GDD) and not by means of the more complex Sarvas function (cf. DP1).

$$S_f(t) = \sum_{i=t_1}^{t} R_f(T_i) \qquad \text{with} \qquad S_f(t_2) := F^* \qquad \textbf{(9.8.12)}$$

$$R_f(T_i) = 0 \qquad \text{for} \qquad T_i \le T_{Bf} \qquad \textbf{(9.8.13)}$$

$$R_f(T_i) = T_i - T_{Bf} \qquad \text{for} \qquad T_i > T_{Bf} \qquad \textbf{(9.8.14)}$$

with
- S_f state of forcing
- R_f forcing rates
- F^* forcing units; heat sum which has to be reached before the phenophase can be started
- T_i daily mean temperature
- T_{Bf} plant-specific base temperature for „forcing"
- t_1 start for calculating F^*
- t_2 smallest whole number where $S_f(t_2) \ge F^*$ is valid; start of the phenophase

The phenological model DP3 is activated by setting the plant-specific method identifier in the extended [landuse_table] to "DynamicPhenology_3". Compared to the previous models (DP1 and DP2), DP3 does not only allow to simulate the starting day of active growth but also the timing of the subsequent phenophases.

The practical use of DP3 requires the definition of so-called "Sample-Days" which indicate the "maximum Julian days" where the actual phenophase should be started at the latest. The "Sample-Days" are plant-specific parameters. They have to be given within the parameter row *(max) JulDays* in the WaSiM-ETH [landuse_table].

The "Samply-Day" entries are closely linked to another newly introduced pheno-parameter, namely the "forcing thresholds". These thresholds (in the WaSiM-ETH control file named as *ForcingThreshold*) have to be defined separately for each "Sample-Day".

WaSiM-ETH interprets positive "Sample-Day" entries as threshold values which have to be reached by the "forcing rates" (R_f). In the case that R_f reaches the *ForcingThreshold* earlier than the corresponding "Sample-Day", the actual Julian day is used as start day of the new phenophase. In the other case (the *ForcingThreshold* is not reached earlier than the corresponding "Sample-Day") the given "Sample-Day" is taken as new start day.

It is important to know that the first and last "Sample-Day" entries cannot be calculated dynamically but have to be fixed to 1 and 366, respectively. In both cases, the corresponding *ForcingThresholds* have to be set to -1.

In general, "Sample-Days" are interpreted as fixed if the corresponding *ForcingThresholds* are set to -1. Then plant growth can only be influenced by its altitude dependency.

WaSiM-ETH linearly interpolates between “Sample-Days”. It can be discriminated between two scenarios:

Scenario 1: The next “Sample-Day” is fixed.

Here the temporal interpolation is done linearly by using the Julian-Day entries of the actual (fixed or dynamic) and next (fixed) “Sample-Days”.

Example: The leaf area index (LAI) between day 60 (with LAI = 2) and day 100 (with LAI = 10) is interpolated to 4 at day = 70.

Scenario 2: The next “Sample-Day” is calculated dynamically.

Here the temporal interpolation considers both the reached “forcing rates” of the actual (fixed or dynamic) and the *ForcingThresholds* of the subsequent “Sample-Day”.

Example: The LAI between day 60 (with S_f = 200 and LAI = 2) and the next (uncertain) day (with *ForcingThreshold* = 600 and LAI = 10) is interpolated to 4 at S_f = 300.

WaSiM-ETH does not allow using DP3 without having the parameter entries for DP1 and DP2. The simulated Julian days indicating the start and the end of the phenophases can be controlled by a data stack which is written at the end of the model run. The stack is labelled as “MultipleStartTimes1_End” and contains phenological information for each „Sample-Day“. In addition the actual state of forcing (S_f) is saved in stack layer 0.

9.8.4 Considering the influence of soil moisture on phenology

A stress factor has been introduced into the [landuse_table] of WaSiM-ETH in order to simulate the influence of soil moisture on phenological development. The factor is labelled as *StressFactorDynPhen* and can be defined separately for each landuse type. As seen in Equation 9.8.15 the stress factor is used as scaling parameter for the forcing units (F^*).

$$F^{*}{}' = F^{*} \cdot StressFactorDynPhen \cdot \left(\frac{\Psi(t) - HReduDry}{150 - HReduDry} \right) \qquad \textbf{(9.8.15)}$$

with F^* forcing units; heat sum which has to be reached before the actual phenophase can be started

ψ actual hydraulic head (calculated by using the van Genuchten parameters of the upper soil layer and the mean soil water content of the rooted soil zone)

HReduDry hydraulic head for beginning dryness stress (reduction of transpiration)

The stress factor can influence the plant development in two different ways: a) Stress values larger than 1 will probably accelerate the phenology, whereas a deceleration can be expected for values smaller than 1. No phenological stress occurs in the case of missing or negative stress factor values (the same is valid for *StressFactorDynPhen* = 0). As far as our experience goes an useful range for the stress factor is between 0.5 and 2.

9.8.5 Handling of phenological output data

The results of the phenological simulation can be saved and controlled by using the writegrid options in the section [variable_grids] of the WaSiM-ETH control file. The model allows creating outputs for the the following variables (outputs for each vegetation layer):

- SumOfForcingUnits (for DP1, DP2 and DP3)
- Pheno_start (for DP1, DP2 and DP3)
- SumOfChillingUnits (for DP2)
- FStar_ForcingThreshold (for DP2 and DP3)

Furthermore, the above-mentionend grid outputs can also be used for the initialization of (serial) model runs (option $DPreadgrids with: 0 = initialize internally, 1 = read in from grid).

```
# extract from section [variable_grids] for vegetation layer 1

$outpath//$forcingunitsgrid1      SumOfForcingUnits1              0 -1
$Writegrid
$DPreadgrids
$outpath//$TStartPhenoGrid1       Pheno_start1                    0 -1
$Writegrid
$DPreadgrids
$outpath//$chillingunitsgrid1     SumOfChillingUnits1             0 -1
$Writegrid
$DPreadgrids
$outpath//$FStargrid1             FStar_ForcingThreshold1         0 -1
$Writegrid
$Dpreadgrids
```

The both codes shown behind the grid names have the following meaning:

The first code indicates if "nodata values" should be replaced automatically by "nearest neighbor values" (0 = no, 1 = yes). The second code informs if a grid should be read in or internally initialized. For the phenological variables the latter code is set to -1 per default because this signalizes WaSiM-ETH that threshold values have not been reached yet.