Appendix 4.1

Additional hydraulic functions available in Daisy

This appendix describes all the sub-models to the <hydraulic> module in Daisy that has not been included in Chapter 4. This includes Brooks and Corey-based models, and van Genuchten-based models, several of which are dual porosity-models. Also included are table formats, an attempt to include hysteresis, an attempt to include tillage effects, and a function for test of the numerical integration of hydraulic conductivity required for the Richards' equation.

It is commonly found that fitting hydraulic functions using a measured value for unsaturated hydraulic conductivity produces an estimate of K_s that at quite different from the measured K_s. The dual porosity models generally attempt to solve the problem that there is a significant drop in hydraulic conductivity values from saturation to wet unsaturated conditions. However, a few of the models also consider the dry end of the retention- and hydraulic conductivity curves.

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1 Inverse modelling option

1.1 B_C_inverse

The function calculates the parameters for a Cambell retention curve with Burdine theory based on specified points on the retention curve and hydraulic conductivity curve. Values that can be specified are θ_s, θ_{fc} (water content at field capacity (pF = 2)), θ_{wp} (water content at wilting point (h = -15000 cm, pF = 4.176))), K_s, and K_at_h with a value for K at a specified pressure. The last two parameters are optional; only one of the two are specified.

If θ_s is not specified, it is calculated based on either dry bulk density or porosity. In the first case,

$$\theta_s = 1 - \frac{\rho_{soil}}{\rho_{texture}} \tag{1}$$

where

ρ_{soil} = bulk density of soil [g cm^{-3}], and

$\rho_{texture}$ = bulk density calculated based on texture fractions [g cm^{-3}].

If θ_{wp} is not specified, it is calculated based on Breuning Madsen and Platou (1983) as

$$\theta_{wp} = (0.758 \cdot OM + 0.520 \cdot Cl + 0.075 \cdot Si + 0.42)/100 \qquad r = 0.970,\ s = 1.63/100 \tag{2}$$

where OM, Cl and Si (2-20 µm) are humus (organic matter), clay and silt [%] according to the ISSS3 textural classification.

There is no default for water content at field capacity. However, Breuning Madsen and Platou (1983) has an equation for this value too:

$$\theta_{wp} = (2.888 \cdot OM + 0.490 \cdot Cl + 0.455 \cdot Si + 0.164 \cdot fS + 2.376)/100 \qquad r = 0.894,\ s = 4.32/100 \tag{3}$$

where fS is fine sand (20-200 µm).

2 van Genuchten curve adapted for dry conditions: BW-VGM/ MvGBS

2.1 The retention curve

The Brunschwick version of the van Genuchten retention curve model with Mualem (Mualem, 1976) and Tokunga (Tokunaga, 2009; Weber et al., 2019) theory for hydraulic conductivity (BW-VGM) is implemented in Daisy with the name *M_vGBS.* The BW-VGM-model divides the soil water retention and the hydraulic conductivity into a capillary part and a non-capillary part. Thus, the soil water retention is the sum of the capillary and non-capillary functions given by:

$$\theta(h) = \theta_{cs} S_c(h) + \theta_{ncs} S_{cn}(h) \tag{4}$$

where:

θ_{cs} and θ_{ncs} are the saturated water contents of the capillary and the noncapillary parts, respectively, and

$S_c(h)$ and $S_{nc}(h)$ are the saturation as a function of pressure head, h, for the capillary and non-capillary part.

The capillary saturation function, $S_c(h)$, is described by the van Genuchten model (Chapter 4, eq.9) and the noncapillary saturation function is given by:

$$S_{nc}(h) = 1 - \frac{S_{nc}^*(h)}{S_{nc}^*(h_0)} \tag{5}$$

where:

h_0 = the pressure head at which oven dryness is attained (default pF 6.8) and

S_{nc}^* is the effective saturation function of the noncapillary part expressed as:

$$S_{nc}^*(h) = \log_{10}(e) \int_h^{-10\varepsilon} \frac{S_C(h') - 1}{h'} dh' \tag{6}$$

where h' denotes the dummy variable of integration and -10^ε, the upper boundary of the integral, is a pressure head value very close to zero. This part is not implemented directly in Daisy but calculated with lookup tables.

2.2 Hydraulic conductivity

Similar to the water retention curve, the hydraulic conductivity curve is divided into a capillary and non-capillary part. The capillary part is described with the analytical solution to the van Genuchten-Mualem model (Chapter 4, eq. 15) by Streck and Weber (2020). The hydraulic conductivity for the noncapillary part is based on the new noncapillary saturation function (eq. 7). It builds on the theory from Tokunaga on hydraulic conductivity of absorbed water films and is expressed as:

$$K_{nc}(S_{nc}) = K_{snc}\left(\frac{|h_0|}{h_r}\right)^{-af(1-S_{nc})} \tag{7}$$

where:

K_{snc} = the "maximum unsaturated" hydraulic noncapillary conductivity [cm h^{-1}], with a default of 0.000793942 cm h^{-1} based on the result from Weber et al. (2020),

h_r = 1 [cm], ensuring matching dimensions and

af = a parameter which governs the slope of the hydraulic conductivity curve in the part of the function where noncapillary flow dominates. It has a default of 1.5 [-] based on Weber et al. (2019).

2.3 Pedotransfer function: HYPWEB

HYPWEB PTF is a two-step pedotransfer function for the BW-VGM water retention and hydraulic conductivity curves (eq. 4 - 7). First HYPRES (Eq. 4.20-4.24) is used to generate parameter for the van Genuchten-Mualem retention curve and hydraulic conductivity curve (Chapter 4, eq. 9 and 15) based on clay (< 2 µm) [%], silt (2-50 µm) [%], organic matter [%], bulk density [g cm^{-3}] and a distinction between top- and subsoil. Based on these parameters, the parameters, θ_{cs}, α, n and λ for the BW-VGM water retention and hydraulic conductivity curves are generated as described by Weber et al. (2020). θ_{ncs} is given as input or calculated based on a θ_r-value of 0.01.

$$\theta_{ncs} = -1.58 * 10^{-3} + 1.285 * \theta_{r,VGM} \tag{8}$$

$$\theta_{tot} = 1.89 * 10^{-3} + 0.993 * \theta_{s,VGM} \tag{9}$$

$$\log_{10}\alpha_{BW} = -2.06 * 10^{-2} + 0.986 * \alpha_{VGM} \tag{10}$$

$$\log_{10} n_{BW} - 1 = 6.42 * 10^{-2} + 0.933 * \log_{10} n_{VGM} - 1 \tag{11}$$

$$\log_{10} K_{s,BW} = 1.16 * 10^{-1} + 1.060 * \log_{10} K_{s,VGM} \tag{12}$$

$$l_{BW} = 2.95 * 10^{-2} + 1.833 * l_{VGM} \tag{13}$$

where:$_{BW}$ are parameters in the BW-VGM model and $_{VGM}$ are parameters in the van Genuchten-Mualem water retention and hydraulic conductivity curves. l_{BW} is only given by l_{VGM} when $l_{VGM} \geq$ 0, for $l_{VGM} <$ 0, $l_{BW} =$ 0. As K_{snc} has no corresponding parameter in the VGM-model, the median (0.000793942 [cm h^{-1}]) of K_{sc} estimated for 1.729 soil samples by Weber et al. (2020), is used.

3 Bimodal models adapted for wet conditions

3.1 Brooks and Corey-based models

3.1.1 B_BaC_Bimodal

The bimodal function applies the Brooks and Corey retention curve with Burdine theory to pressures below h_b. The water content at h_b is θ_b and the hydraulic conductivity is K_b. Between h_b and saturation ($h=0$), θ and K are calculated using the following functions:

$$\theta = \frac{\theta_s - \theta_b}{(-h_b)} \cdot (h - h_b) + \theta_b \tag{14}$$

$$K = \frac{K_s - K_b}{(-h_b)} \cdot (h - h_b) + K_b \tag{15}$$

where

θ = water content [-],

θ_s = water content at saturation [-],

θ_b =water content at bubbling pressure [-],

h = soil water pressure [cm],

h_b = bubbling pressure [cm],

K = hydraulic conductivity [cm h^{-1}],

K_s = hydraulic conductivity at saturation [cm h^{-1}],

K_b = hydraulic conductivity at bubbling pressure [cm h^{-1}].

3.1.2 M_BaC_Bimodal

The bimodal function applies the Brooks and Corey retention curve with Mualem theory to pressures below h_b. The water content at h_b is θ_b and the hydraulic conductivity is K_b. Between between h_b and saturation ($h=0$), θ and K are calculated using the following equation (14) and (15) above.

3.2 van Genuchten based models

3.2.1 MACRO

NB: This option is not operational at the moment.

The MACRO option (Larsbo and Jarvis, 2003) describes a micropore-domain using Richard's equation and the van Genuchen retention curve model with Mualem theory to calculate the vertical water flux in the micropores. The near saturated retention and hydraulic properties have been adjusted to take macropores into account. Water flow in the macropore domain is calculated by gravity: The governing equation for water flow in macropores is:

$$\frac{\partial \theta_{ma}}{\partial t} = \frac{\partial K_{ma}}{\partial z} - \sum S_i \tag{16}$$

where θ_{ma} and K_{ma} are the macropore water content and hydraulic conductivity, respectively. Since K_{ma} is assumed to be a power law function of θ_{ma}, this approach to describe water flow in macropores is equivalent to the kinematic wave approach to macropore flow described by Germann (1985).

In microporous soils, hydraulic conductivity increases very rapidly across a small pressure head range as saturation is approached (Clothier and Smettem (1990); Jarvis and Messing (1995)). In MACRO, this macropore/micropore dichotomy is dealt with using a “cut and join” approach to defining the hydraulic functions (Jarvis, (1991); Wilson et al. (1992); Mohanty et al. (1997)). A user-defined “breakpoint” or “boundary pressure head (ψ_b) partitions the total porosity into micro- and macroporosity, while a corresponding water content (θ_b) and hydraulic conductivity (K_b) represent the saturated state of the soil matrix.

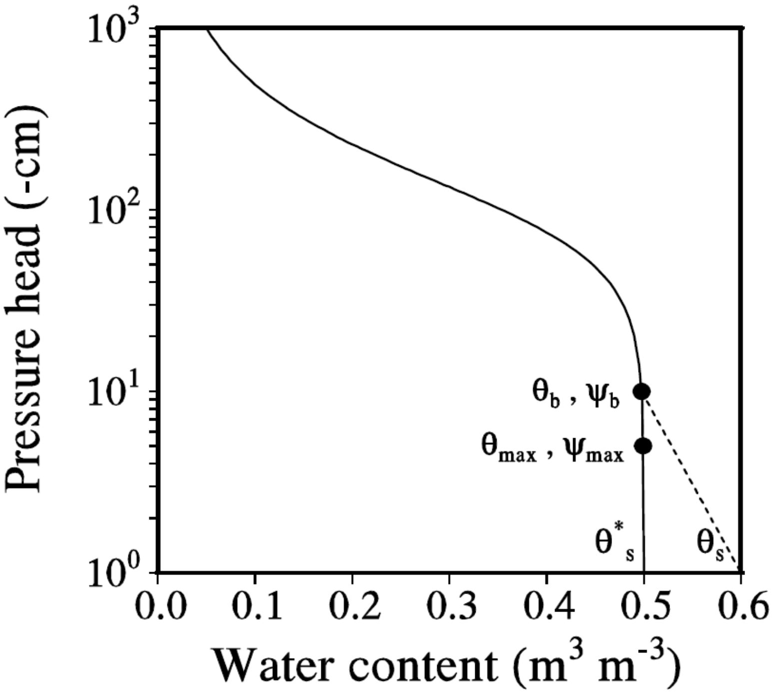


Figure 1. Modified van Genuchten soil water retention function used in MACRO5.0 (α_{vg} = 0.01 cm^{-1}, n_{vg} = 2, θ_r = 0.0 and θ^*_s = 0.05 m^3 m^{-3}.

Soil water retention in the micropores is calculated using a modified form of van Genuchten's, (1980) equation:

$$S = \frac{\theta_{mi} - \theta_r}{\theta_s^* - \theta_r} = \left(1 + \left(\alpha_{vg}\psi\right)^{n_{vg}}\right)^{-m_{vg}} \tag{17}$$

where S is an effective water content, m_{vg}, n_{vg} and α_{vg} are shape parameters (where m_{vg} is fixed equal to $(1\text{-}1/n_{vg})$. θ_r is the residual water content and θ^*_s is a "fictitious" saturated water content, obtained by fitting eq. 17 to retention data for pressure heads less than ψ_b. θ^*_s does not represent the actual saturated water content in the model, as this is separately defined by the user to reflect the microporosity. Rather, it is only used internally in the program to extend the retention curve to pressure head values larger than ψ_b to allow for temporary oversaturation in the micropores when solving Richard's equation.

Mualem's (1976) model is used to describe the unsaturated hydraulic conductivity function in the micropores, with the "matching point" hydraulic conductivity given as K_b (Luckner et al., 1989):

$$K_{mi} = K_b \left(\frac{S}{S_{mi(\theta_b)}}\right)^l \left[\frac{\left(1-\left(1-S^{1/m_{vg}}\right)^{m_{vg}}\right)}{\left(1-\left(1-S_{mi(\theta_b)}{}^{1/m_{vg}}\right)^{m_{vg}}\right)}\right]^2 \qquad (18)$$

where l is the tortuosity factor in the micropores, and $S_{mi(\theta_b)}$ is given by:

$$S_{mi(\theta_b)} = \left(1+\left(\alpha_{vg}\psi_b\right)^{n_{vg}}\right)^{-m_{vg}} \qquad (19)$$

The hydraulic conductivity function in the macropores is given as a simple power law expression of the macropore degree of saturation, S_{ma}:

$$K_{ma} = K_{s(ma)}(S_{ma})^{n^*} \qquad (20)$$

where $n*$ is a "kinematic exponent reflecting macropore size distribution and tortuosity, and:

$$S_{ma} = \frac{\theta_{ma}}{e_{ma}} \qquad (21)$$

where θ_{ma} is the macropore water content and e_{ma} is the microporosity equivalent to the total saturated water content θ_s minus θ_b.

The MACRO model contains an additional function taking into account swelling/shrinking of the macropore domain as well as tillage effects. This is not included in this option.

In Daisy, θ_s, $K_{s,ma}$, θ_r, θ_b, ψ_b, K_b, n_{vg}, n^*, and l are specified as input parameters. θ^*_s is calculated from eq. 17, where the right side of the equation is calculated based on ψ_b, and θ^*_s can be found from re-arranging the equation. The functions are enabled by including *enable_K_macro* true (include contribution from macropores in conductivity curve) and *enable_Theta_macro* true (include contribution from macropores in retention curve).

3.2.2 M_BivG: Bimodal van Genuchten retention curve model with Mualem theory.

This submodule builds on an article by Durner (1994), describing how different retention curves can be superimposed, taking into account different groups of pore sizes. The maximum pore space is still θ_s, so each retention curve is weighted, and the sum of the weights must be 1. This Daisy option allows inclusion of two van Genuchten retention curves that are parameterized with the usual parameters, but where α and n are different for the two curves. A weight is specified for the second curve.

Durner (1994) describes the calculation of a relative hydraulic conductivity, K_{rel}, based on the combined retention curve as:

$$K_{rel} = S_e^l \left[\frac{f(S_e)}{f(1)}\right]^2 \tag{22}$$

where f is given by

$$f(S_e) = \int_0^{Se} \frac{1}{\psi(S_e')}\, dS_e' \tag{23}$$

S_e is the relative saturation, and l is the tortuosity factor. The relative "K_{rel}" is then scaled by K_s or by a value of K measured at a given pressure.

3.2.3 M_vG_compact: van Genuchten retention curve model with Mualem theory and compaction.

The purpose of this model is to be able to adjust the hydraulic parameters as a function of the porosity of the soil. The porosity is changed by some external factor. The soil has the standard parameters for the van Genuchten/Mualem calculation (θ_s, θ_r, α, n, K_s) for the reference conditions, and plf-functions for the modifiers to α, n, and K_s as functions of porosity. The modified θ_s is equal to the adjusted porosity. The new value of α is calculated as $\alpha_{ref} \cdot f_\alpha(\theta_s)$, and n and K_s are treated similarly. Tortuosity is not an input for this function, so the Mualem value of 0.5 for l is assumed.

NB: The function has not been tested.

3.2.4 M_vGip: Modified (Ippisch) van Genuchten retention curve model with Mualem theory.

This submodule follows the description by Ippisch et al. (2006) where an air-entry value is introduced in the van Genuchten-equation. Ippisch et al. (2006) states that introduction of an air entry value is required if $n<2$ or $\alpha \cdot h_a>1$, where $h_a = 2\sigma_w/(\rho_w \cdot g \cdot R_{max})$ (σ_w = the surface tension at the air-water interface, ρ_w = the density of water at reference temperature, g = the gravity constant and R_{max} = the radius of the biggest conducting pore).

The standard van Genuchten model

$$S_e = [1 + (\alpha h)^n]^{-m} \tag{24}$$

is re-written as

$$S_e = \begin{cases} \frac{1}{S_C} \cdot [1 + (\alpha h)^n]^{-m} & h > h_e \\ 1 & h \le h_e \end{cases} \tag{25}$$

where h_e is the air entry value used in the model, best found through optimization, and

$$S_C = [1 + (\alpha h_e)^n]^{-m} \tag{26}$$

Similarly, the expression for relative hydraulic conductivity (K_{rel}) (Mualem-van Genuchten):

$$K_{rel} = S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{27}$$

is re-written to

$$K_{rel} = \begin{cases} S_e^l \cdot \left[\dfrac{1 - \left(1 - (S_e S_C)^{\frac{1}{m}}\right)^m}{1 - \left(1 - (S_C)^{\frac{1}{m}}\right)^m}\right]^2 & S_e < 1 \\ 1 & S_e \geq 1 \end{cases} \tag{28}$$

The relative hydraulic conductivity can then be scaled using K_s or the conductivity at a specified pressure. Compared to the normal Mualem-van Genuchten-solution, only the h_e-parameter has to be specified additionally.

3.2.5 M_vGp: Modified (Børgesen) van Genuchten retention curve model with Mualem theory.

Børgesen et al. (2006) proposed a method to overcome the discrepancy between the measured K_s and K_s obtained by fitting the hydraulic conductivity curve to unsaturated measurements of K, caused by biomodality of the pore domains. They proposed a new empirical scaling function to scale the conductivity functions in the near saturated region:

$$p_m = \begin{cases} \left(\dfrac{1}{|h|\chi + 1}\right)^f, & h > h_m \\ \left(\dfrac{1}{|h_m|\chi + 1}\right)^f, & h \leq h_m \end{cases} \tag{29}$$

The h_m [hPa] parameter can be interpreted as the boundary between pressure heads at which macropore flow or matrix flow dominates. χ=1 hPa^{-1} is a constant to make the scaling factor dimensionless. Without prior knowledge on pore size boundary between the two domains, the h_m parameter is a fitting parameter and the f-parameter is a curve shape parameter of the conductivity function.

The conductivity model thus changes to:

$$K(S_e) = K_0 \cdot S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^\gamma \cdot p_m \tag{30}$$

K_0 is a matching factor, while p_m is constant for $h<h_m$, giving predictions similar to optimizing K_0 in the vGM model. γ equals 2 for the Mualem implementation and cannot be set separately in this Daisy option. The advantages of this approach are that the hydraulic conductivity curve becomes smooth at the interconnections at $h = h_m$ and that it always starts at the measured saturated hydraulic conductivity. This solution requires specification of f and h_m in addition to the normal van Genuchten/Mualem parameters. K_s requires specification, while measurement(s) of K under unsaturated conditions must be used for calibration of the two extra parameters f and h_m, which are given as input to the submodule.

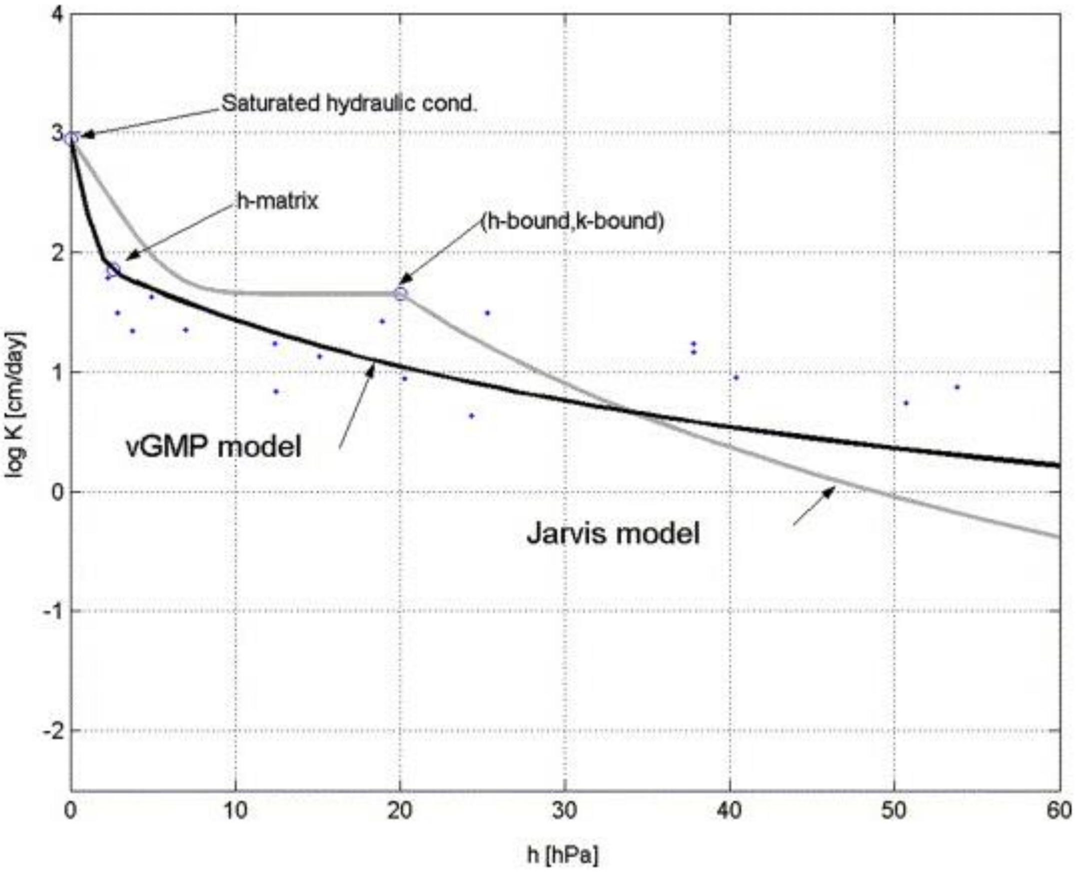


Figure 2. Fig. 3 from Børgesen et al. (2006). The Jarvis model and the improved van Genuchten–Mualem model (vGMP) calibrated (method M2) to the saturated and unsaturated hydraulic conductivity measurements for a sandy subsoil (3% clay). h-matrix is the vGMP parameter h_m*, both h-boundary and k-boundary are the Jarvis parameter* h_b and k_b*, respectively.*

3.3 Hyprop: Curve fitting method used by the HYPROP software (PDI)

3.3.1 Retention curves

This method is developed by Peters (2013) and Iden and Durner (2014), and is described in the HYPROP-FIT User's manual, Appendix 3 (Peters and Durner, 2015). It is also abbreviated "the PDI-model". It differs from the earlier methods in that it considers two domains for the retention curve (capillary and adsorptive) but three domains for hydraulic conductivity. The domains considered for hydraulic conductivity are the capillary domain, which dominates above field capacity, the film flow domain, which dominates down to the wilting point and the vapour domain, which dominates from about a decade below the wilting point (pressure in [cm]). There are transition zones between the domains. The description below is based entirely on the mentioned publications.

The model presented by Peters (2013) expresses soil water content θ [-] as function of suction h [L] by superimposing an expression for capillary storage and an expression for water storage caused by adsorption of water at solid surfaces. Iden and Durner (2014) reformulated Peters' (2013) model of the retention curve as:

$$\theta(h) = (\theta_s - \theta_r) \cdot S_{cap}(h) + \theta_r \cdot S_{ad}(h) \qquad (31)$$

where $S_{cap}(h)$ [-] is the relative saturation of capillary water and $S_{ad}(h)$ [-] is the relative saturation of adsorbed water. θ_r is the maximum content of adsorbed water.

The capillary domain can be parameterized by classic approaches like van Genuchten or models accounting for multimodality of the pore-size distribution. Daisy allows the use of the Durner-method (Durner, 1994), also implemented as M_BivG (Section 3.2.2 above). Thus, the capillary domain can be described by two different van Genuchten-curves weighed together.

Iden and Durner (2014) suggested the following equation to describe the relative saturation of adsorbed water:

$$S_{ad} = 1 + \frac{1}{x_a - x_0}\left\{x - x_a + b \cdot ln\left[1 + exp\left(\frac{x_a - x}{b}\right)\right]\right\} \tag{32}$$

where

x = $log_{10}(h)$, $x_0=log_{10}(h_0)$, $x_a=log_{10}(h_a)$ and b [-] is a smoothing parameter

h_0 = the water pressure after oven drying at 105°C. The water content is considered 0 and the default value is -6.30957e+06 [cm]

h_a = the upper boundary for pressure in the adsorptive domain, which is the pressure where S_{cap} = 0.5. Can also be expressed as the pressure at air entry for the adsorptive domain.

In combination with the van Genuchten retention model, b is expressed as:

$$b = 0.1 + \frac{0.2}{n^2}\left\{1 - exp\left[-\left(\frac{\theta_r}{\theta_s - \theta_r}\right)\right]\right\} \tag{33}$$

and h_a can be expressed as

$$h_a = \frac{\left(2^{1/m} - 1\right)^{1/n}}{\alpha} \approx \frac{1}{\alpha} \tag{34}$$

If the capillary domain is described by two van Genuchten-curves (Durner, 1994), the two functions are weighed together with weights, subject to $0<w_i<1$ and $\Sigma w_i=1$. (Note, that Peters, (2013) also uses a “*w*” in his formulation, but not for the same function). For calculation of *b* and h_a for the bimodal function, *n* is taken from the subfunction with highest value for α or the lowest value for h_m.

To ensure that the sum in eq. (31) becomes 0 at h_0, the fitted model for the capillary domain ($\Gamma(h)$) must be forced to 0 at h_0. This is done by the following rescaling of $\Gamma(h)$:

$$S_{cap}(h) = \frac{\Gamma(h) - \Gamma(h_0)}{1 - \Gamma(h_0)} \tag{35}$$

This correction causes hardly any changes in coarse textured soils, but plays a role for finer textured soils, mainly in the dryer end of the retention curve.

3.3.2 Hydraulic conductivity

Peters (2013) describes the liquid conductivity as the sum of the conductivity from capillary flow (cap) and film flow (film). This is expressed as:

$$K_{rel}^{liq}(S) = (1 - \omega)K_{rel}^{cap}(S^{cap}) + \omega K_{rel}^{film}(S^{ad}) \tag{36}$$

where K_s^{cap} and K_s^{film} are capillary and film conductivity at saturation given by $K_s^{film} = \omega \cdot Ks$ and $K_s^{cap} = (1-\omega) \cdot K_s \approx K_s$. This equation can then be scaled to the hydraulic conductivity function for the liquid phase by multiplying with the total saturated hydraulic conductivity, K_s, or by fitting to a conductivity value at a given h.

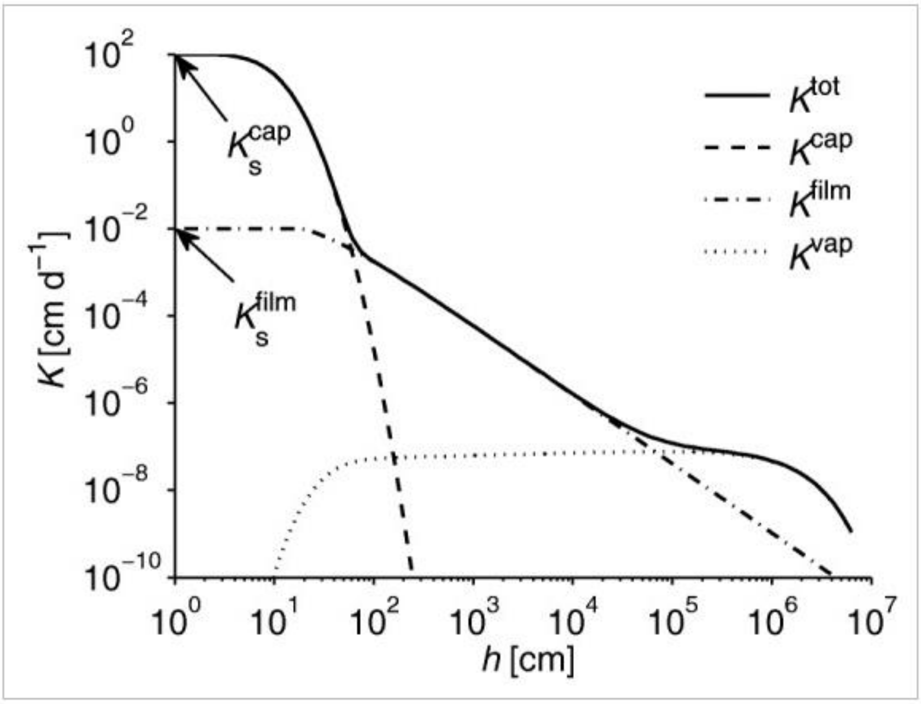


Figure 3. Figure 4 from Peters (2013). Exemplary illustration of the contribution of capillary, film, and vapor components to the proposed hydraulic conductivity model. For parameter values, please see the original article.

Relative conductivity for capillary flow is described by the pore bundle model of Mualem, which for the capillary retention function is given by:

$$K_{rel}^{cap}(S^{cap}) = (S^{cap})^{\tau}\left[\frac{\int_0^{S^{cap}} \frac{1}{h} dS^{cap*}}{\int_0^{1} \frac{1}{h} dS^{cap*}}\right]^2 \tag{37}$$

where τ [-] is tortuosity and connectivity-factor (½ in Mualem's original interpretation and similar to l in e.g. eq. (22) or (27)) and S^{cap^*} is a dummy variable of integration.

Assuming that the capillary domain is described by a van Genucten curve, the relative hydraulic conductivity for this domain can be described as:

$$K_{rel}^{cap}(S^{cap}) = (S^{cap})^{\tau}\left[1-\left(1-(S^{cap})^{1/m}\right)^{m}\right]^2 \tag{38}$$

where $m = 1\text{-}1/n$.

For the bimodal van Genuchen function, the solution can be written as:

$$K_{rel}^{cap} = \left(\sum_{i=1}^{k} w_i S_i^{cap}\right)^{\tau}\left[1-\frac{\sum_1^2 w_i\alpha_i\left(1-\mathit{\Gamma}_i^{1/m_i}\right)^{m_i}}{\sum_1^2 w_i\alpha_i\left(1-\mathit{\Gamma}_{0,i}^{1/m_i}\right)^{m_i}}\right]^2 \tag{39}$$

The relative conductivity for film flow is expressed as:

$$K_{rel}^{film}(S_{ad}) = \left(\frac{h_0}{h_a}\right)^{a(1-S_{ad})} \tag{40}$$

where a [-] is the slope on the log-log-scale. The value of a is found to be approximately 1.5 (Peters, 2013).

The hydraulic conductivity due to vapor flow is given by (Saito et al., 2006):

$$K^{vap} = \frac{\rho_{sv}}{\rho_w D}\frac{M \cdot g}{R \cdot T}H_r \tag{41}$$

where

K_{vap} = isothermal vapor hydraulic conductivity [m s^{-1}]

ρ_{sv} = saturated vapor density of water [kg m^{-3}]

ρ_w = liquid density of water (1000 kg m^{-3})

M = the molecular weight of water (0.018015 kg mol^{-1})

g = the gravitational acceleration (g = 9.81 m s^{-2}),

R = the universal gas constant (R = 8.314 J mol^{-1} K^{-1}),

T = The absolute temperature(K),

D = the vapor diffusivity (m^2 s^{-1}), and

H_r = the relative humidity [-].

D is dependent on water content and is calculated according to (Saito et al., 2006):

$$D = \zeta \cdot \theta_a \cdot D_a \tag{42}$$

where θ_a is the volumetric air content, D_a (m^2 s^{-1}) is the diffusivity of water vapor in air and ζ is the tortuosity factor for gas transport, calculated according to Millington and Quirk (1961):

$$\zeta = \frac{\theta_a^{7/3}}{\Phi^2} \tag{43}$$

where ϕ is the porosity, here assumed to be equal to θ_{sat}. D_a and ρ_{sw} depends on temperature:

$$D_a = 1.14 \cdot 10^{-5}\left(\frac{T}{273.15}\right)^2 \tag{44}$$

$$\rho_{sv} = 10^{-3} exp\left(31.3716 - \frac{6014.79}{T} - 7.92495 \cdot 10^{-3}T\right)T^{-1} \tag{45}$$

H_r is calculated with the Kelvin equation:

$$H_r = exp\left(-\frac{p \cdot M \cdot g}{R \cdot T}\right) \tag{46}$$

where p is pressure in [m].

The total hydraulic conductivity is given by:

$$K = K_S\left[(1-\omega)K_{rel}^{cap}(S^{cap}) + \omega K_{rel}^{film}(S^{ad})\right] + K^{vap} \tag{47}$$

where all values for hydraulic conductivity should be kept in the same units (e.g. m s^{-1}, cm d^{-1} or cm h^{-1}).

4 Table formats

4.1 Old2

This format is obsolete and should be avoided in new projects. It is a file with four columns in the format < *pF Theta Cw2 K* >. *pF* is water pressure (*log(-h)* [cm]), *Theta* (θ [-]) is the water content at that pressure, *Cw2* is $d\theta/dh$ at the specified pressure [cm^{-1}] and K is the water conductivity (K) at the specified pressure [cm h^{-1}]. The file must contain exactly 501 lines, pF starting at 0 and increasing with the same increment in each line. In line 500, pF is thus 500 ”increment”. The default value for the increment is 0.01 [pF], but it can be modified. The number of intervals used for numeric integration of K [*M_intervals*] is by default 500.

The file does not have a heading, so units must be as specified above.

4.2 table

“table” reads a ddf file with columns defining *pF*, *Theta*, *Cw2* and K. pF is water pressure (*log(-h)* [cm]), *Theta* (θ [-]) is the water content at that pressure, *Cw2* is $d\theta/dh$ at the specified pressure [cm^{-1}] and K is the water conductivity (K) at the specified pressure [cm h^{-1}]. A ddf-file starts with a line introducing the file type and content:

```
ddf-0.0 – Hydraulic data for Taastrup A-horizon
```

This may be followed by more explanatory text:

```
# The data were measured by method X for depth 5-10 cm.
```

followed by the file content:

```
---
pF     Theta     Cw2      K
                 cm       cm/h
0      0.40      0.05     1.0
```

etc.

The function is called by specifying (hydraulic table (file filename))

A number of parameters can be specified with the function. These are:

- The number of intervals used for numeric integration of K (*M_intervals*, by default 500),
- *Theta_res*, (θ_{res} [-]), the soil residual water content. It is by default 0.
- A list of strings indicating how missing values are indicated in the file. This parameter has, by default, a length of 2 (*missing* “ “ “00.00”).
- a filter function that can define that only rows that pass all set filters can be included. By default, there are no filters.
- The units of the data in the data file can be specified as a string (the optional parameter “*original*” must be specified and the optional parameter “*dim_line*” must be set to “false”. However, by default it is assumed that the line after the tags (headings) will contain dimensions (*dim_line* is “true” by default).

5 Hysteresis

5.1 Linear

An attempt was done to include hysteresis by linear transformation implemented as:

$$\theta^*(h) = a * \theta(h) + b \text{ and } K^*(h) = c * K(h) + d \tag{48}$$

where:

θ = the water content defined by either the water retention curve describing the wetting phase (wet in Daisy) or the water retention curve describing the drying phase (dry in Daisy).

K = the conductivity defined by either the hydraulic conductivity curve describing the wetting phase (*wet* in Daisy) or the hydraulic conductivity curve describing the drying phase (*dry* in Daisy) and

a, b, c and d = factors and offsets multiplied or added to the water content and hydraulic conductivity, respectively. The factors (a and c) are recalculated whenever the node switches between wetting and drying. Whether a, b, c and d are applied during wetting or drying is controlled by the state variable *is_wetting*. If *is_wetting* is true a, b, c and d are applied to the *wet* model.

The model has never been tested.

6 Inclusion of tillage effects

6.1 wepp

This submodule only contains a few of the functions from the WEPP- model (Water Erosion Prediction Project). The documentation for the WEPP model is available on https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/wepp-model-documentation/ . The process descriptions included here are described in Chapter 7 of the documentation (Alberts et al., 1995).

In the original WEPP model, points on the hydraulic curves are calculated when changes happen in the soil. I Daisy, new hydraulic parameters are calculated based on the HYPRES model as a function of fixed texture and organic material but adjusted bulk density.

6.1.1 Bulk density

The bulk density changes over time. WEPP considers a consolidated bulk density, loosening due to tillage, consolidation due to rainfall and time, and loosening due to frost.

6.1.1.1 *Consolidated bulk density*

The consolidated bulk density ρ_c [kg m^{-3}] is described in Alberts et al. (1995) as

$$\rho_c = (1.514 + 0.25 \cdot sand_f - 13.0 \cdot sand_f \cdot OM_f - 6{,}0 \cdot clay_f \cdot om_f - 0{,}48 \cdot clay_f \cdot CECr) \cdot 10^3 \tag{49}$$

The consolidated bulk density is the density, which the soil gradually, through consolidation, will go towards after tillage considering that it is not influenced by traffic, frost, or root growth.

The textural fractions are calculated as follows:

$$clay_f = \%\ clay/(\%\ clay + \%silt + \%\ sand + \%\ SOM)$$
$$silt_f = \%\ silt/(\%\ clay + \%silt + \%\ sand + \%\ SOM)$$
$$sand_f = \%\ sand/(\%\ clay + \%silt + \%\ sand + \%\ SOM)$$

$$OM_f = \% \, SOM/(\% \, clay + \%silt + \% \, sand + \% \, SOM)$$

$CECr$ is CEC for clay [cmol kg^{-1}] is an optional parameter in Daisy. Krogh et al. (2000) mentions that the average CEC for the organic fraction is about 284-291 cmol kg^{-1} and for clay it is 48-53 cmol kg^{-1} (=mmol/100 g clay). If set, the value should thus be 50 cmol kg^{-1}. The total amount of CEC attributed to the clay is then:

$$CECc = CECr \cdot clay_f$$

if it is not set, it is calculated according to the WEPP-equation (7.7.3),

$$CECc = CEC - OM \cdot (142.0 + 170.0 \cdot Dg) \qquad (50)$$

where Dg is the average depth in [m], CEC is in [meq/100 g], and $CECr$ is found by division by $clay_f$.

In this option, CEC can be specified for a horizon. By default, CEC [cmol kg^{-1}] is calculated according to Krogh et al. (2000), who developed the following equation for Danish soils:

$$CEC = 0.95 + 2.90 \cdot \% \, SOM + 0.53 \cdot \% \, clay \qquad r_2 = 0.90 \qquad (51)$$

This equation is not identical to the original WEPP equation for CEC.

6.1.1.2 Bulk density just after tillage

The bulk density just after soil tillage is described in WEPP as suggested by Williams et al. (1984):

$$\rho_{tet} = \rho_t - 1 - [(\rho_t - 1 - 0{,}667 \cdot \rho_c) \cdot T_{ds}] \qquad (52)$$

where

ρ_{tet} = bulk density just after tillage [kg m^{-3}]

ρ_{t-1} = bulk density just before tillage [kg m^{-3}]

ρ_c = consolidated bulk density [kg m^{-3}]

T_{ds} = A factor that depends on how large a fraction of the surface is affected by tillage (Alberts et al., 1995, table 7.5.1) and Table 4.1.2 below.

If tillage is carried out several times, the calculation is repeated. In Daisy, the factor “0.667” has been made a calibration factor, K_1:

$$\rho_{tet} = \rho_t - 1 - [(\rho_t - 1 - K_1 \cdot \rho_c) \cdot T_{ds}] \qquad (53)$$

This change makes it possible to make the effect of different treatments a function of soil moisture and to describe the effect of traffic (wheel tracks) with the same equation. Petersen et al. (2016) showed that both soil moisture and traffic influenced the bulk density:

$$K_1 = \alpha \cdot ((\theta(t) - \theta_{min})/(\theta_{max} - \theta_{min})) + \beta \qquad (54)$$

where $\theta(t)$ is the actual water content [$m^3 \, m^{-3}$] and θ_{max} and θ_{min} are the maximum and minimum water content acceptable for soil tillage. α and β are parameters depending on tillage method. In Petersen et al. (2016), θ_{max} and θ_{min} were reported to be 0.34 and 0.1, respectively, and values of α and β for their experiment are shown in Table 4.1.1. Both values can be specified in the sub-module.

Table 4.1.1. Consolidated bulk density and suggested parameterization of K_1 for the soil at Rørrendegård for different types of tillage and traffic (Petersen et al., 2016).

Plot	Description	Organic matter, %	ρ_c, [kg m^{-3}]	α	β
F1	2*stubble harrowing (6 cm), row sowing	3.43	1343	0	0.81
F2	Direct sowing (disc cutter)	3.43	1350	0	0.845
F2, tracks	Tracks due to tillage/sowing			0.14	1
	Tracks, other traffic			0.14	1
F3	Ploughing, furrow packing, rotary harrowing (5 cm), row sowing	2.47	1431	-0.093	0.845
F4	Ploughing, seed bed harrowing (spring tines), row sowing	2.47	1439	-0.069	0.88
F4, tracks	Tracks due to tillage/sowing			0.1	1
	Tracks, other traffic			0.1	1

6.1.1.3 Consolidation due to rain and time

According to WEPP, the maximum increase in bulk density ($\Delta\rho_{mx}$ [kg m^{-3}]) due to precipitation (as rain) can be predicted from the equation (Onstad et al., 1984):

$$\Delta\rho_{mx} = 1650 - 2900 \cdot clay_f + 3000 \cdot clay_f^2 - 0.92 \cdot \rho_{tet} \tag{55}$$

The actual consolidation due to rain can be calculated as $\Delta\rho_{rf}$ with the unit [kg m^{-3}]:

$$\Delta\rho_{rf} = \begin{cases} \Delta\rho_{mx} \cdot \dfrac{R_c}{0.01 + R_c} & 0 < R_c \leq 0.100\ [m] \\ \Delta\rho_{mx} \cdot \dfrac{0.100}{0.01 + 0.100} & R_c > 0.100\ [m] \end{cases} \tag{56}$$

where R_c is the accumulated rainfall. Accumulated rainfall (R_c [m]) at the time t (days) from the time of tillage ($t=0$) is calculated as:

$$R_c(t) = R(t) + R_c(t-1) \tag{57}$$

where $R(t)$ is daily rainfall at the time $t > 0$.

ρ_{d100} is the expected bulk density after tillage and 0.1 m of rain:

$$\rho_{d100} = \rho_{tet} + \Delta\rho_{max} \cdot \frac{0.100}{0.01 + 0.100} \qquad R_c > 0.100\ [m]$$

The possible consolidation as function of time, $\Delta\rho_c$, when the effect of 100 mm rain is considered is in WEPP defined as:

$$\Delta\rho_c = \begin{cases} \rho_c - \rho_{d100} & \rho_c - \rho_{d100} > 0 \\ 0 & \rho_c - \rho_{d100} \leq 0 \end{cases} \tag{58}$$

The consolidation as function of time is then calculated as:

$$\Delta\rho_{wt} = \Delta\rho_c \cdot F^{ds} \tag{59}$$

where

$$F_{ds} = 1\text{-}eksp(K_2 \cdot Daycnt(t)) \tag{60}$$

K_2 is a calibration parameter which in WEPP is given a value of 0.005 d^{-1}. $Daycnt$, the time since last tillage,is calculated as

$$Daycnt(t) = 1 + Daycnt(t-1) \tag{61}$$

The calculated consolidation as a function of the first 100 mm rainfall after tillage (ρ_{d100}) can in some cases be larger than the upper boundary, which is the consolidated bulk density (ρ_c). The possible consolidation as function of time, $\Delta\rho_c$, when the effect of 100 mm rain is considered is in WEPP defined as:

$$\Delta\rho_c = \begin{cases} \rho_c - \rho_{d100} & \rho_c - \rho_{d100} > 0 \\ 0 & \rho_c - \rho_{d100} \leq 0 \end{cases} \tag{62}$$

The bulk density at the time t after tillage (ρ_t [kg m^{-3}]) is then calculated as the sum of the bulk density just after tillage (ρ_{tet}), consolidation as a function of rain ($\Delta\rho_{rt}$) and consolidation as function of time ($\Delta\rho_{wt}$). The values of $\Delta\rho_{max}$. and $\Delta\rho_c$ are re-calculated after tillage.

According to Petersen et al. (2016), the value of $\Delta\rho_{max}$ is calculated by the WEPP-equation is much larger than what was found in their experiment. In their experiment it was approximately 80 kg m^{-3} and constant over the 2 years.

$\Delta\rho_c$ cannot be negative in WEPP. Petersen et al. (2016) observed negative time consolidation in wheel tracks. In this subfunction, a Boolean parameter can be set *(allow negative delta pc true)* that allows $\Delta\rho_c = \rho_c - \rho_{tet}$ if $(\rho_c - \rho_{d100})$ is negative.

6.1.1.4 Changes in bulk density due to frost

The bulk density of soil is typically reduced due to frost because the formation of ice increases the volume of water. The effect of frost is taken into account by reducing the consolidation by rainfall by the frost effect, which makes up about 80-100 kg m^{-3}. Only the rainfall induced consolidation is reduced, not the consolidation by time. The adjustment takes place when the amount of frozen water in the topmost calculation cell is larger than a specified value. In Petersen et al. (2016), this value was found to be 19 vol. %. If the rainfall consolidation in the last timestep is larger than the effect of freezing (Frost, (kg m^{-3}]), an adjusted rainfall amount is calculated ($R_{adjusted}$ [mm]) which represents the new consolidation level.

If $\Delta\rho_{rf}(t-1) - Frost > 0$: (63)

$$R_{adjusted} = (\Delta\rho_{rf}(t-1) - Frost) \cdot 0.01/(\Delta\rho_{mx} - (\Delta\rho_{rf}(t-1) - Frost))$$

$$\Delta\rho_{rf\text{-}adjusted} = \Delta\rho_{mx} * R_{adjusted}/(0.01 + R_{adjusted})$$

else $R_{adjusted} = 0$

R_{adjust} is the start value for the summarized R for the next time-steps.

6.1.2 Water retention properties

The WEPP model has its own calculation of water content at specific suction values, but in this sub-module, the retention properties are calculated using HYPRES based on the specified texture, organic matter content and adjusted bulk density. Thus, the properties for a van Genuchten retention curve are generated and used to describe the water retention. The curve is updated for every timestep based on the adjusted bulk density.

6.1.3 Hydraulic conductivity

The hydraulic conductivity calculated by HYPRES is used in the model. The curve is updated every timestep based on the adjusted bulk density. Thus, the submodule does not use the hydraulic conductivity calculated by the WEPP-functions.

WEPP uses Green and Ampt infiltration, and in this sub-module, K_{bare} (see below) is calculated according to the WEPP equations and can be logged for comparison.

Hydraulic conductivity is influenced by tillage and typically reduced over time due to crust formation on the surface. This is described in WEPP using the following equation:

$$K_{bare} = K_b\left[CF + (1 - CF)e^{-C\cdot E_a(1-RR_i/0.04)}\right] \tag{64}$$

where K_{bare} and K_b are the effective conductivity for any given event and the baseline hydraulic conductivity [mm h^{-1}], respectively, CF is a crust factor which ranges from 0.20 to 1, C is a soil stability factor [m^2 J^{-1}], E_a is the cumulative kinetic energy of the rainfall since the last tillage operation [J m^{-2}], and $RR(t)$ is the random roughness of the soil surface [m]. K_b represents a freshly tilled or maximum hydraulic conductivity, which will decrease exponentially at a rate proportional to the kinetic energy of the rainfall since last tillage as it approaches the fully crusted or final value.

The crust factor, CF, provides a means of estimating the final or fully crusted hydraulic conductivity based on the baseline values. The fully crusted hydraulic conductivity is simply the baseline value multiplied by the crust factor. A relationship developed by Rawls et al. (1990) states that:

$$CF = \frac{SC}{1 + \frac{\Psi}{100\,L}} \tag{65}$$

where SC is the correction factor for partial saturation of the subcrust, Ψ is the steady state capillary potential at the crust/subcrust interface and L is the wetted depth [m]. They also derive the following expressions for SC and Ψ:

$$SC = 0.736 + 00.19\,sand_f \tag{66}$$

$$\Psi = 45.19 - 46.68\,SC \tag{67}$$

The depth to the wetting front (L) is calculated in the WEPP model as:

$$L = 0.147 - 0.15\left(sand_f\right)^2 - 0.0003\left(clay_f\right)\rho_b \tag{68}$$

where ρ_b is the bulk density [kg m^{-3}]. If the calculated value of L is less than the crust thickness (0.005 [m] in WEPP), then it is set equal to the crust thickness.

The soil stability factor C [m^2 J^{-1}], is estimated as:

$$C = -0.0028 + 0.113 \cdot sand_f + 0.125 \cdot \left[\frac{clay_f}{CEC}\right] \tag{69}$$

where CEC is in meq/100 g. Bounds of $0.0001 < C < 0.010$ were imposed on the equation to prevent negative C-values on soils with very low sand and clay contents. The equation predicts that soils with high amounts of sand and clay and low CEC will form crusts more rapidly.

E_a is the accumulated rainfall energy. Rainfall energy is calculated as $E = 11.9 + 8.73 \cdot log(I)$ (Wischmeier and Smith, 1978), where the rainfall intensity I is in [mm h^{-1}] and E is in [J m^{-2} mm^{-1}]. The energy must be multiplied with the amount of rain (R_i [mm]) in the respective time interval (typically 1.0 h in Daisy) to obtain the kinetic energy for the rainfall event [J m^{-2}]:

$$E_i = (11.9 + 8.73 \cdot log(I_i)) \cdot R_i \tag{70}$$

The energy for a single day, (E(t)) is the sum of the energy in time intervals with rain for that day. The accumulated energy from the time of tillage, $Ea(t)$ is calculated as:

$$E_a(t)=E_a(t-1) + E_a(t) \tag{71}$$

The energy is set to 0 at tillage and is regulated due to frost.

Random roughness ($RR(t)$ [m]) describes the coarseness of the surface at the time t. A coarse surface takes longer to break down due to impact by rain. $RR(t)$ just after tillage (RRi [m]) is calculated as

$$RRi = RR_0 \cdot T_{ds} + RR(t-1) \cdot [1-T_{ds}] \tag{72}$$

where $RR(t-1)$ is the random roughness just before tillage, RR_0 [m] and T_{ds} [-] are values given for different types of tillage ((Alberts et al., 1995, table 7.5.1) and table 4.1.2 below). RR_0 is the Random Roughness that, based on experience, is created by the specific tilling tool and T_{ds} is the fraction of the surface that is affected.

The random roughness over time is then described as a function of "buried residue" (*br*) in 0-15 cm's depth [kg m^{-2}] and the content of clay and organic matter in the soil:

$$RR(t) = RRi * exp[(-C_{br} \cdot ((R_c \cdot 1000)/b)^{0.6}] \tag{73}$$

where

R_c = accumulated rainfall after tillage [m],

C_{br} $=1 - 0.5 \cdot br$, and

b $=63 + 62.7 \cdot ln(50 \cdot OM_f) + 1570 \cdot clay_f - 2500 \cdot clay_f^2$

br is set to minimum 0.3 [kg m^{-2}] in WEPP. In our equation, a factor of 1000 is included, which is not present in the WEPP documentation. Without this factor, the roughness becomes almost static. We expect it to be a unit error (R_c in [m] instead of [mm]).

K_b [mm h^{-1}] is calculated according to the following equations:

For soils with ≤ 40 % clay

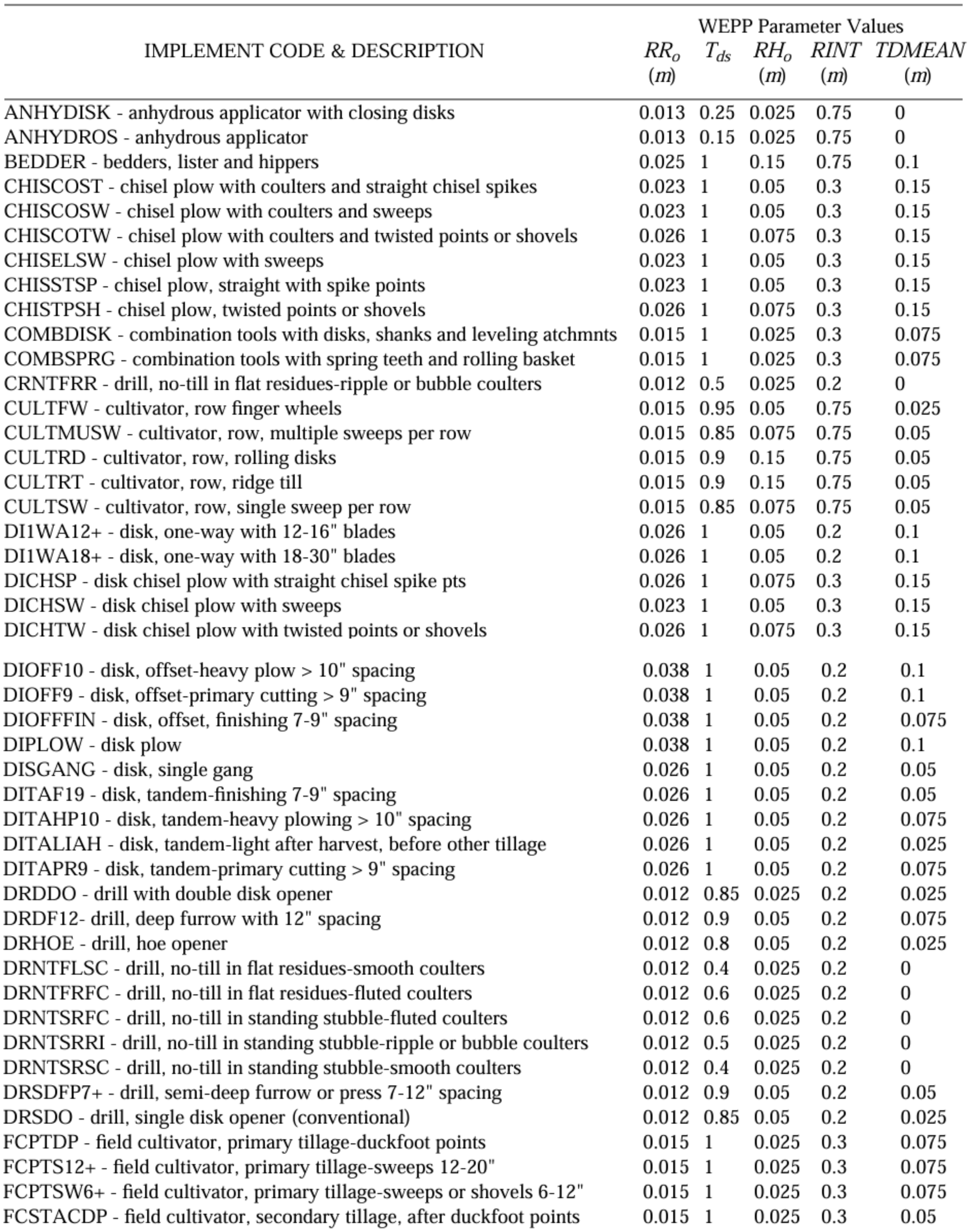
$$K_b = -0.265 + 0.0086 \cdot \left(100 \ \cdot sand_f\right)^{1.8} + 11.46 \cdot CEC^{-0.75} \tag{74}$$

For soils with < 40 % clay

$$K_b = 0.0066 \cdot e^{\left[\frac{2.44}{clay_f}\right]} \tag{75}$$

In this sub- module, K_b is set to 10.0 if CEC ≤ 1 meq/100 g, which is extremely low.

Table 4.1.2. Table 7.5.1 from (Alberts et al., 1995): WEPP soil parameters for 78 implements.



IMPLEMENT CODE & DESCRIPTION	WEPP Parameter Values				
	RR_o (m)	T_{ds}	RH_o (m)	$RINT$ (m)	$TDMEAN$ (m)
ANHYDISK - anhydrous applicator with closing disks	0.013	0.25	0.025	0.75	0
ANHYDROS - anhydrous applicator	0.013	0.15	0.025	0.75	0
BEDDER - bedders, lister and hippers	0.025	1	0.15	0.75	0.1
CHISCOST - chisel plow with coulters and straight chisel spikes	0.023	1	0.05	0.3	0.15
CHISCOSW - chisel plow with coulters and sweeps	0.023	1	0.05	0.3	0.15
CHISCOTW - chisel plow with coulters and twisted points or shovels	0.026	1	0.075	0.3	0.15
CHISELSW - chisel plow with sweeps	0.023	1	0.05	0.3	0.15
CHISSTSP - chisel plow, straight with spike points	0.023	1	0.05	0.3	0.15
CHISTPSH - chisel plow, twisted points or shovels	0.026	1	0.075	0.3	0.15
COMBDISK - combination tools with disks, shanks and leveling atchmnts	0.015	1	0.025	0.3	0.075
COMBSPRG - combination tools with spring teeth and rolling basket	0.015	1	0.025	0.3	0.075
CRNTFRR - drill, no-till in flat residues-ripple or bubble coulters	0.012	0.5	0.025	0.2	0
CULTFW - cultivator, row finger wheels	0.015	0.95	0.05	0.75	0.025
CULTMUSW - cultivator, row, multiple sweeps per row	0.015	0.85	0.075	0.75	0.05
CULTRD - cultivator, row, rolling disks	0.015	0.9	0.15	0.75	0.05
CULTRT - cultivator, row, ridge till	0.015	0.9	0.15	0.75	0.05
CULTSW - cultivator, row, single sweep per row	0.015	0.85	0.075	0.75	0.05
DI1WA12+ - disk, one-way with 12-16" blades	0.026	1	0.05	0.2	0.1
DI1WA18+ - disk, one-way with 18-30" blades	0.026	1	0.05	0.2	0.1
DICHSP - disk chisel plow with straight chisel spike pts	0.026	1	0.075	0.3	0.15
DICHSW - disk chisel plow with sweeps	0.023	1	0.05	0.3	0.15
DICHTW - disk chisel plow with twisted points or shovels	0.026	1	0.075	0.3	0.15
DIOFF10 - disk, offset-heavy plow > 10" spacing	0.038	1	0.05	0.2	0.1
DIOFF9 - disk, offset-primary cutting > 9" spacing	0.038	1	0.05	0.2	0.1
DIOFFFIN - disk, offset, finishing 7-9" spacing	0.038	1	0.05	0.2	0.075
DIPLOW - disk plow	0.038	1	0.05	0.2	0.1
DISGANG - disk, single gang	0.026	1	0.05	0.2	0.05
DITAF19 - disk, tandem-finishing 7-9" spacing	0.026	1	0.05	0.2	0.05
DITAHP10 - disk, tandem-heavy plowing > 10" spacing	0.026	1	0.05	0.2	0.075
DITALIAH - disk, tandem-light after harvest, before other tillage	0.026	1	0.05	0.2	0.025
DITAPR9 - disk, tandem-primary cutting > 9" spacing	0.026	1	0.05	0.2	0.075
DRDDO - drill with double disk opener	0.012	0.85	0.025	0.2	0.025
DRDF12- drill, deep furrow with 12" spacing	0.012	0.9	0.05	0.2	0.075
DRHOE - drill, hoe opener	0.012	0.8	0.05	0.2	0.025
DRNTFLSC - drill, no-till in flat residues-smooth coulters	0.012	0.4	0.025	0.2	0
DRNTFRFC - drill, no-till in flat residues-fluted coulters	0.012	0.6	0.025	0.2	0
DRNTSRFC - drill, no-till in standing stubble-fluted coulters	0.012	0.6	0.025	0.2	0
DRNTSRRI - drill, no-till in standing stubble-ripple or bubble coulters	0.012	0.5	0.025	0.2	0
DRNTSRSC - drill, no-till in standing stubble-smooth coulters	0.012	0.4	0.025	0.2	0
DRSDFP7+ - drill, semi-deep furrow or press 7-12" spacing	0.012	0.9	0.05	0.2	0.05
DRSDO - drill, single disk opener (conventional)	0.012	0.85	0.05	0.2	0.025
FCPTDP - field cultivator, primary tillage-duckfoot points	0.015	1	0.025	0.3	0.075
FCPTS12+ - field cultivator, primary tillage-sweeps 12-20"	0.015	1	0.025	0.3	0.075
FCPTSW6+ - field cultivator, primary tillage-sweeps or shovels 6-12"	0.015	1	0.025	0.3	0.075
FCSTACDP - field cultivator, secondary tillage, after duckfoot points	0.015	1	0.025	0.3	0.05

FCSTACDS - field cultivator, secondary tillage, sweeps 12-20"	0.015	1	0.025	0.3	0.05
FCSTACSH - field cultivator, secondary tillage, swp or shov 6-12"	0.015	1	0.025	0.3	0.05
FURROWD - furrow diker	0.015	0.7	0.025	0.75	0.05
HAFTT - harrow-flex-tine tooth	0.018	1	0.025	0.1	0.025
HAPR - harrow-packer roller	0.01	1	0.025	0.08	0.025
HARHCP - harrow-roller harrow (cultipacker)	0.01	1	0.025	0.08	0.025
HASP - harrow-spike tooth	0.015	1	0.025	0.05	0.025
HASPTCT - harrow-springtooth (coil tine)	0.015	1	0.025	0.05	0.025
MANUAPPL - applicator, subsurface manure	0.013	0.4	0.025	0.75	0
MOPL - plow, moldboard, 8"	0.043	0.1	0.05	0.4	0.15
MOPLUF - plow, moldboard with uphill furrow (Pacific NW only)	0.043	1	0.05	0.4	0.15
MULCHT - mulch treader	0.015	1	0.025	0.05	0.025
PARAPLOW - paratill/paraplow	0.01	0.3	0.025	0.36	0.2
PLDDO - planter, double disk openers	0.012	0.15	0.025	0.75	0.05
PLNTFC - planter, no-till with fluted coulters	0.012	0.15	0.025	0.75	0
PLNTRC - planter, no-till with ripple coulters	0.012	0.15	0.025	0.75	0
PLNTSC - planter, no-till with smooth coulters	0.012	0.15	0.025	0.75	0
PLRO - planter, runner openers	0.013	0.2	0.025	0.75	0.05
PLRT - planter, ridge-till	0.013	0.4	0.1	0.75	0.05
PLSDDO - planter, staggered double disk openers	0.013	0.15	0.025	0.75	0.05
PLST2C - planter, strip-till with 2 or 3 fluted coulters	0.013	0.3	0.025	0.75	0.05
PLSTRC - planter, strip-till with row cleaning devices (8-14" wide)	0.013	0.4	0.025	0.75	0.05
RORRP - rodweeder, plain rotary rod	0.01	1	0.025	0.13	0.05
RORRSC - rodweeder, rotary rod with semi-chisels or shovels	0.01	1	0.025	0.13	0.05
ROTHOE - rotary hoe	0.012	1	0	0	0.025
ROTILPO - rotary tiller-primary operation 6" deep	0.015	1	0	0	0.15
ROTILSO - rotary tiller-secondary operation 3" deep	0.015	1	0	0	0.075
ROTILST - rotary tiller, strip tillage - 12" tilled on 40" rows	0.015	0.3	0	0	0.075
SUBCC - subsoil-chisel, combination chisel	0.015	1	0.075	0.3	0.4
SUBCD - subsoiler, combination disk	0.015	1	0.075	0.3	0.4
SUBVRIP - subsoiler, V ripper 20" spacing	0.015	0.2	0.075	0.5	0.4
UNSMWBL - undercutter, stubble-mulch sweep (20-30"wide) or blade	0.015	1	0.075	1	0.075
UNSMWBP - undercutter, stubble-mulch sweep or blade plows > 30" wide	0.015	1	0.075	1.5	0.075

6.1.4 Important omissions

The most important omission in this implementation is that the rainfall and energy impact are not corrected for cover by plants or mulch. There are options in the WEPP model to include this, but they have not been implemented.

Using HYPRES to generate parameters based on bulk density does take into account some of the effects linking bulk density and hydraulic conductivity. However, WEPP has a number of functions related to hydraulic conductivity (e.g. crust formation) that are not expected to be taken into account properly in this solution.

6.1.5 Styczen

This model is a sub-model of the wepp-model, with specific parameterization of some of the wepp-parameters. These values were generated in the project “Jordbearbejdningens indflydelse på pesticidudvaskning til markdræn” (Petersen et al., 2016) on Taastrup soil under conventional tillage. In this case, $\Delta\rho_{mx}$ is set to 80 [kg m^{-3}], $CECr$ to 50 [cmol kg^{-1} clay, and negative values of $\Delta\rho_c$ are allowed. Furthermore, $Frost$ is set to 100 [kg m^{-3}], and the limits for turning the frost effect on and off are 0.19 and 0.01 volume fractions of ice.

7 Test of numerical integration of K

7.1 Yolo

This option builds on an article by Haverkamp et al. (1977), describing very detailed measurements of hydraulic conductivity and retention data in a Yolo clay soil. The data supports an analytical solution that can be used to test Richard's equation, particularly the numerical integration of K. The Yolo light clay is described by the following equations:

$$\theta = \frac{\alpha(\theta_s - \theta_r)}{\alpha \cdot (ln|h|)^{\beta}} + \theta_r \tag{76}$$

$$K = K_s \frac{A}{A + |h|^B} \tag{77}$$

where θ_s = 0.495, θ_r = 0.124, α = 739, β = 4 for $h < -1$ cm and $\theta = \theta_s$ for $h > 1$ cm and K_s = 4.428 · 10^{-2} cm h^{-1}, A = 124.6, B = 1.77.

In the article by Haverkamp et al. (1977) a comparison is made between infiltration profiles as calculated with one of six tested numerical schemes and as calculated with the quasi-analytical solutions by Philip (1957) and Parlange (1971) . The only parameter that can be set in this option is the number of intervals specified (M, by default 500) for numerical integration of the functions above.

8 Parameter overview

Table 4.1.3. Related Parameter names in Daisy

Name and explanation		**Model (in Daisy)**	**Parameter name (Daisy reference manual)**	**Default**	**Default unit**
General parameters					
θ_s	Volumetric soil water content at saturation.	Hydraulic, all functions except yolo	*Theta_sat*	User specified	[fraction] [cm^3 cm^{-3}]
θ_r	Residual volumetric soil water content.	Hydraulic, all functions except yolo	*Theta_res*	Generally, default = 0. However, in WEPP, default=0.01.	[fraction]
h_b ψ_b	Bubbling pressure, air-entry value.	B_BaC_Bimodal M_BaC_Bimodal MACRO	*h_b*	User specified	[cm]
θ_b	Water content at bubbling pressure	B_BaC_Bimodal M_BaC_Bimodal MACRO	*Theta_b*	User specified	[-]
λ	Brooks and Corey shape parameter. Pore size index.	B_BaC_Bimodal, M_BaC_Bimodal	*lambda*	User specified	[-]
K_s ($K_{s(ma)}$ eq.29)	Saturated hydraulic conductivity	Hydraulic, all functions except yolo	*K_sat*	User specified	[cm h-^{1}]
K_b	Hydraulic conductivity at h_b	B_BaC_Bimodal, M_BaC_Bimodal MACRO	*K_b*	User specified	[cm h-^{1}]
K_at_h	Hydraulic conductivity at a specified h	B_C_inverse M_BivG	*K_at_h*	Optional parameter (instead of K_s)	[cm h-^{1}]
α (α_{vg})	Van Genuchten shape parameter	MACRO, M_BivG, M_vG_compact, M_vGip, M_vGp, hyprop	*alpha*	User specified	[cm^{-1}]

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
n ***(n_{vg})***	Van Genuchten shape parameter	As above	*n*	User specified	[-]
l ***or*** ***τ***	Tortuosity parameter	MACRO, M_BivG, , M_vGip, M_vGp, hyprop	*L* τ	Default depending on model. Burdine: 2, Mualem: 0.5	[-]
Specialised parameters					
θ_{fc}	Water content at field capacity	B_C_inverse	*Theta_fc*	User specified	*[-]*
θ_{wp}	Water content at wilting point	B_C_inverse	*Theta_wp*	Optional parameter. Default calculation eq. 2.	*[-]*
θ_{cs}	Saturated water content of the capillary part of the retention curve.	M_vGBS	*Theta_cap*	User defined	*[-]*
θ_{ncs}	Saturated water content of the non-capillary part of the retention curve.	M_VGBS	*Theta_np*	User defined	*[-] [fraction]*
h_0	The pressure head at oven dryness.	M_vGBS	*pf0*	6.8	*[-] [pF]*
K_{snc}	The hydraulic noncapillary conductivity.	M_vGBS	*Ks_nc*	0.000793942	*[cm h^{-1}]*
af	Governs the slope of the hydraulic conductivity curve in the part of the function where noncapillary flow dominates.	M_vGBS	*afilm*	1.5	*[-]*
n^*	Macropore size distribution factor, eq. 20.	MACRO	*n_ma*	User specified	[-]
α_1, α_2	Van Genuchten α for two functions	M_BivG	*alpha1, alpha2*	User specified	[cm^{-1}]
n_1, n_2	Van Genuchten n for two functions	M_BivG	*n1, n2*	User specified	[-]

Name and explanation		**Model (in Daisy)**	**Parameter name (Daisy reference manual)**	**Default**	**Default unit**
w_2	Weight of the second function. Weight of the first function will be *(1-w)*	M_BivG	*w2*	User specified	[-]
α_{ref}	Value before compaction	M_vG_compact	*ref_alpha*	User specified	[cm^{-1}]
n_{ref}	Value before compaction	M_vG_compact	*ref_n*	User specified	[-]
$K_{s,ref}$	Value before compaction	M_vG_compact	*ref_K_sat*	User specified	[cm h-^{1}]
$f_\alpha(\theta_s)$	Modifyer function for α	M_vG_compact	*mod_alpha*	Pdf-function linking the altered θ_s to a factor to multiply onto α	[-]
n_{ref}	Value before compaction	M_vG_compact	*ref_n*	User specified	[-]
$K_{s,ref}$	Value before compaction	M_vG_compact	*ref_K_sat*	User specified	[cm h-^{1}]
$f_\alpha(\theta_s)$	Modifyer function for α	M_vG_compact	*mod_alpha*	Pdf-function linking the altered θ_s to a factor to multiply onto α	[-]
$f_n(\theta_s)$	Modifyer function for n	M_vG_compact	*mod_n*	Pdf-function linking the altered θ_s to a factor to multiply onto n	[-]
$f_{Ks}(\theta_s)$	Modifyer function for K_s	M_vG_compact	*mod_K_sat*	Pdf-function linking the altered θ_s to a factor to multiply onto K_s	[-]
h_e	Expression for air entry value/bubbling pressure in eq. 25.	M_vGip	*he*	Default -2 [cm]	[cm]
h_m	Pressure point between matrix and macropores, eq. 29.	M_vGp	*h_m*	User specified	[cm]
f	Macropore conductivity curve shape parameter, eq. 29.	M_vGp	*f*	User specified	[-]
m	Van Genuchten m parameters for each van Genuchten curve applied (see also section 2.2)	hyprop	*m*	By default (1-(1/n)) sequence	[-]

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
h_a	Pressure at air entry for the adsorptive retention, eq. 34.	hyprop	*ha*	By default, 1/max(alpha)	[cm]
α *(more values)*	Van Genuchten α parameters for each van Genuchten curve applied.	hyprop	*alpha*	sequence	[cm^{-1}]
a	Slope of relative conductivity for film flow, log-log scale, eq. 40.	hyprop	*a*	Default: -1.5	[-]
n *(more values)*	Van Genuchten n parameters for each van Genuchten curve applied	hyprop	*n*	Sequence	[-]
h_0	Water pressure after oven drying at 105°C	hyprop	*h0*	-6.30957e+06	[cm]
w	Weight of each van Genuchten retention curve parameterised	hyprop	*w*	User specified fractions, sum must be =1	[fraction]
ω	Weight of film conductivity to the total relative liquid conductivity	hyprop	*omega*	User specified fraction	[fraction]
τ	Tortuosity parameter for the capillary domain	hyprop	*tau*	User specified	[-]
Function: Linear, eq.48.					
a	Factor multiplied with the water content	linear	*a*	User specified	[ ]
b	Offset added to water content	linear	*b*	User specified	[cm^3 cm^{-3}]
c	Factor multiplied with hydraulic conductivity	linear	*c*	User specified	[ ]
d	Offset added to hydraulic conductivity	linear	*d*	User specified	[cm h^{-1}]
	A normal hydraulic component has to be selected as either the wet or the dry soil, as basis for	linear	*wet*	User specified	
		linear	*dry*	User specified	

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
	the calculation, typically the drying soil.				
	State variable. True, if the a, b, c, and d-factors are applied to the “wet” model.	linear	*is_wetting*	User specified	
K_1	Consolidation factor, eq. 53) in relation to tillage. see also β below.	wepp	*consolidate_factor*	Default 0.667	[-]
α	A factor multiplied onto the relative water content, eq. 54, to generate K_1 as function of water.	wepp	*Consolidate_factor_water*	Default 0	[-]
β	If K_1 is a function of water, β is the consolidation factor used in eq. 54.	wepp	*consolidate_factor*	See K_1	[-]
$\Delta\rho_{mx}$	Maximum increase in bulk density due to rain.	wepp	*delta_pmx_fixed*	Optional parameter, for default see eq. 55	[kg m^{-3}]
			delta_pmx	and state variable	
		Styczen	*delta_pmx_fixed*	default: 80	
K_2	Consolidation factor due to time, eq. (60).	wepp	*time_consolidation*	0.005	[d^{-1}]
Dg	Average depth, used for estimation of CECc (eq. 50) and CECr, if unspecified.	wepp	*Average_depth*	Optional parameter. Average depth of horizon. If unspecified, the value from “Soil” is used	[cm]
CECr	Ratio of the cation exchange capacity of the clay to the clay content. Used for calculation of consolidated bulk density, if unspecified.	wepp	*CECr*	Optional parameter. By default, calculated from eq. 50 and the clay content.	[Cmol kg clay]
		Styczen		Default: 50	

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
ρ_c	Consolidated dry bulk density after rain and time.	wepp	*Consolidated_bulk_density*	Optional parameter, by default calculated by eq. 49.	[kg m^{-3}]
ρ_t	Dry bulk density after last tillage	wepp	*p_t*	Optional state variable. By default, this will be consolidated dry bulk density per wepp.	[kg m^{-3}]
$\Delta\rho_c$	Potential dry bulk density change due to time, eq. 4.1.48	wepp	*delta_pc*	State variable (default 0)	[kg m^{-3}]
	Boolean value, determining whether $\Delta\rho_c$ may be negative.	wepp	*Allow_negative_delta_pc*	Default: false	
		Styczen		Default: true	
RRi	Random roughness after last tillage, eq. 72.	wepp	*RRi*	State variable (default 0)	[m]
br	Buried residue 0-15 cm depth since last tillage.	wepp	*br*	State variable (default 0.3)	[kg DM m^{-2}]
crust thickness	Thickness of soil layer that form crust after rain.	wepp	*crust_thickness*	Default: 0.005	[m]
Daycnt(t)	Number of days since last tillage	wepp	*Day_count*	State variable	[d]
$R_c(t)$	Rain since last tillage, eq. 62	wepp	*R_c*	State variable	[m]
$E_a(t)$	Energy in rain since last tillage, eq.71.	wepp	*E_a*	State variable	[J m^{-2}]
RR(t)	Random roughness, eq. 73.	wepp	*RRt*	State variable	[m]
Frost	Maximum decrease of bulk density from frost. Eq. 63	wepp	*freeze-effect*	Parameter, user specified (default 0]	[kg m^{-3}]
		Styczen		Default 100	
	Volumetric ice content above which the frozen state is activated.	wepp	*freeze-on*	Parameter, user specified (default 1)	[fraction]
		Styczen		Default: 0.19	

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
	Volumetric ice content, below which the frozen state is deactivated.	wepp	*freeze-off*	Parameter, user specified (default 0)	[fraction]
		Styczen		Default: 0.01	

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