Parameterization and Application of Regional Hydro-Ecologic Simulation System (RHESSys) for Integrating the Eco-hydrological Processes in the Gwangneung Headwater Catchment

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(Received March 12, 2007; Accepted June 11, 2007)

ABSTRACT
Despite the close linkage in changes between the ecological and hydrological processes in forest ecosystems, an integrative approach has not been incorporated successfully. In this study, based on the vegetation and hydrologic data of the Gwangneung headwater catchment with the Geographic Information System, we attempted such an integrated approach by employing the Regional Hydro-Ecologic Simulation System (RHESSys). To accomplish this, we have (1) constructed the input data for RHESSys, (2) developed an integrated calibration system that enables to consider both ecological and hydrological processes simultaneously, and (3) performed sensitivity analysis to estimate the optimum parameters. Our sensitivity analyses on six soil parameters that affect streamflow patterns and peak flow show that the decay parameter of horizontal saturated hydraulic conductivity ($s_1$) and porosity decay by depth (PD) had the highest sensitivity. The optimization of these two parameters to estimate the optimum streamflow variation resulted in a prediction accuracy of 0.75 in terms of Nash-Sutcliffe efficiency ($NS_e$). These results provide an important basis for future evaluation and mapping of the watershed-scale soil moisture and evapotranspiration in forest ecosystems of Korea.

Key words: RHESSys, Eco-hydrological process, Streamflow, Sensitivity analysis, Parameterization

I. INTRODUCTION
In forest ecosystems, the ecological and hydrological processes are closely connected to each other. Tree growth and leaf onset determine the evaporation from min interception and transpiration through stomata. Tree mortality and root growth influence the structure of soil, increase an amount of organic matters, and improve the capability of water retention within the soil. In turn, soil water content and soil organic matters affect the growth of vegetations in forest ecosystems. Despite the significant role of forest vegetation, most hydrological models roughly consider the ecological processes, which is insufficient to explain the complex ecohydrological processes mentioned above. For example, TOPMODEL that has been applied for the prediction of outflow at
small catchments uses potential evapotranspiration and root zone water storage to predict the evapotranspiration (Kim et al., 2001), without considering the changing response of vegetation to hydrological processes. Similarly, to estimate outflow and water quality within watershed, SWAT employs the simplified seasonal variation and dynamics of vegetation (Santhi et al., 2005).

In order to overcome the limitations and integrate both hydrological and ecological processes, we introduced a carbon-water-nutrient integrated model, called Regional Hydro-Ecologic Simulation System (RHESSys) (Band et al., 1993). RHESSys is a hydro-ecological model designed to simulate integrated water, carbon, and nutrient cycles and transport over spatially variable terrains. The current version of RHESSys continues to follow the basic BIOME-BGC (BIOME-BioGeochemical Cycles) framework for carbon and nutrient processes (Running and Hunt, 1993), while soil moisture redistribution through saturated throughflow and associated runoff production are modeled using either a quasi-spatially distributed model, TOPMODEL, or an explicit routing model which is a modification of the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994). Over a decade, the estimation of carbon-water state and flux in RHESSys has been improved by the outcomes of many researches. (Tague and Band, 2001a, 2001b, 2004). The research subjects were the estimations of the eco-hydrological processes at the small catchment in the North America, an extension of the spatial scale (Baron et al., 1998), the effect of climate change in eco-hydrological processes (Band et al., 1996), and the prediction of evapotranspiration and canopy conductance (Mackay et al., 2003). The RHESSys has been applied and assessed in Europe recently (Zierl et al., 2006) and also in Korea using the KoFlux data since 2003.

In this study, we applied RHESSys to a catchment at the Gwangneung KoFlux site for model parameterization to support evaluation of spatial and temporal variations of ecohydrological processes. The purposes of this study were (1) to construct the input data for RHESSys, based on ground-truth measurements of leaf area index (LAI) and biomass increment, (2) to develop an integrated calibration system to deal with both ecological and hydrological processes simultaneously, and (3) to identify an optimal parameter set of RHESSys for the Gwangneung catchment. Based on the integrated parameterization, we then assessed the suitability and usefulness of the RHESSys.

II. MATERIAL AND METHODS

2.1. Study area

The study catchment is located within the Korea Experimental Forest and Study area.
National Arboretum, Pocheon-si, Gyeonggi-do, Republic of Korea (N37°45' and E127°9'). It is covered with a deciduous broadleaf forest dominated by Quercus serrata, Carpinus laxiflora and Carpinus cordata with ages from 80 to 200 years old and a canopy height about 18 to 20 m. The area of the catchment is about 22 ha (Fig. 1) and was registered as a Long-Term Ecological Research (LTER) site in 1998 and the KoFlux site in 2002 (Lim et al., 2003).

In the study area, a growing season is typically from March to October. Generally, the leaf onset is around 100th day of year and a terminal day of defoliation is around 270th day in 2002-2003 at this study site, but this is variable depending on annual climate variability (Kang et al., 2003; Barr et al., 2004). Annual precipitation is about 1,483 mm from 1982 through 2005. Rain falls intensively between July and August during which much of the rainfall directly runs off into streams over land surface. Thus, we have a handicap for water resources management in Korea.

At the Gwangneung catchment, the Korean Forest Research Institute (KFRI) has monitored stream flow of the 22-ha study catchment since 1982. Also, there are numerous field data including LAI, biomass increment by tree-ring, long-term Diameter at Breast Height (DBH) measurement, chemical content of leaf and soil, soil respiration, soil moisture content, hydrochemical measurements, and flux tower eddy covariance measurements on evapotranspiration and net ecosystem carbon exchange from 2002 to 2005. In this study, we utilized biomass increment (from 1991 to 2004) and annual maximum LAI (3.6; Lim et al., 2003) to initialize carbon state and then parameterize hydraulic conductivity with the measured streamflow data from 1991 to 1999.

2.2. Eco-hydrological processes in RHESSys

RHESSys is composed of the ecological model (BIOME-BGC) focused on photosynthesis and tree growth, the hydrological models (TOPMODEL and DHSVM) that explain vertical and lateral movement of water within the catchment, and the climate model (MTCLIM) that generates the additional climate data based on the limited climate data. The climate model is connected with the other models through providing the climatic data and the ecological/hydrological models are integrated through sharing LAI and canopy conductance. Soil water content influences upon canopy conductance related with discharge of water (Fig. 2).

The Farquhar model is used to calculate photosynthesis. Total evaporative fluxes include evaporation of water intercepted by canopy and transpiration from vegetation. Both evaporation and transpiration rates are computed using the Penman-Monteith combination equation. Canopy conductance is computed based upon the Jarvis' multiplicative model of stomatal conductance where the maximum conductance is scaled by the environmental factors (i.e., radiation, CO₂, leaf water potential, and vapor pressure deficit). The model divides the canopy into two-layer system according to the direct radiation and sunlit/shaded specific leaf area (SLA). The model is operated in a daily time step. The Appendices 1 and 2 show the values of the main parameters used for photosynthesis and evapotranspiration modeling.

After interception loss and evapotranspiration, soil water runs off depending on soil physical characteristics (Fig. 3). RHESSys includes selective hydrological modules, a semi-distributed model (TOPMODEL), and a distributed model (DHSVM). In this study, we focused on the prediction of the streamflow curve through the TOPMODEL.

2.3. Prediction of Streamflow

RHESSys has parameters of vertical and horizontal hydraulic conductivity in soils. Because the soil hydraulic parameters have a large spatial heterogeneity, and since it is very difficult to directly derive the values from in situ measurement (McDonnell and Woods, 2004), we applied sensitivity analysis to find the optimum values of the vertical and horizontal calibration parameters by comparing model results against the measured streamflow data.

For each daily time step, net throughfall was allowed to infiltrate into the soil following Phillip's infiltration equation (Eqs. 1 and 2; Phillip, 1957) and then, the surface runoff was determined as:
Infiltration =

\[ I \times t_p + S_p \times \sqrt{t_d - t_p} + (K_{sat} \times sv_2) \times (t_d - t_p) \]  

where 

- \( I \) is throughfall (in m);
- \( S_p \), sorptivity;
- \( t_d \), throughfall duration (in s);
- \( t_p \), time for water retention (in s);
- \( sv_2 \), parameter for vertical \( K_{sat} \) (saturated hydraulic conductivity, in m d\(^{-1}\));
- \( sv_1 \), parameter for vertical \( m \) (i.e. \( K_{sat} \) decay parameter by depth); and
- \( z \), depth.

Infiltrated water runs off into streams as the baseflow.

**TOPMODEL** estimates saturated subsurface flow (base flow in m d\(^{-1}\)) in hillslopes by using topographical wetness index and soil physical characteristics (Eqs. 3, 4, Eqs 3, 4, and 5). **TOPMODEL** assumes that (1) the saturated hydraulic conductivity decreases exponentially by soil depth, (2) the slope of the water table (saturated depth) is parallel with that of the ground surface, and (3) the water state within the catchment continues the steady state at every time-step.

**Fig. 3.** Main hydrological processes in a forest ecosystem.

**Table 1.** The Range of soil parameters used for sensitivity analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Default</th>
<th>Min. value</th>
<th>Max. value</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.435</td>
<td>0.395</td>
<td>0.500</td>
<td>0.002</td>
</tr>
<tr>
<td>Porosity decay by (soil) depth (PD)</td>
<td>4000</td>
<td>1</td>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>s_1 (multiplier for horizontal m)</td>
<td>1</td>
<td>0.01</td>
<td>10</td>
<td>0.10</td>
</tr>
<tr>
<td>s_2 (multiplier for horizontal K_{sat})</td>
<td>1</td>
<td>0.02</td>
<td>5</td>
<td>0.20</td>
</tr>
<tr>
<td>sv_1 (multiplier for vertical m)</td>
<td>1</td>
<td>0.01</td>
<td>20</td>
<td>0.50</td>
</tr>
<tr>
<td>sv_2 (multiplier for vertical K_{sat})</td>
<td>1</td>
<td>0.02</td>
<td>5</td>
<td>0.20</td>
</tr>
</tbody>
</table>

where \( Q_0 \) is discharge (in m d\(^{-1}\)) at the saturated state; \( SD_{effective} \), effective saturated deficit (water equivalent capillary fringe height in m); \( s_1 \), parameter for horizontal \( m \); \( s_2 \), parameter for horizontal \( K_{sat} \); and \( TWI \) mean, average topographic wetness index in the hillslope.

After computing saturated subsurface flows in hillslopes, the saturated deficit for each patches is redistributed by the **TWI** fraction (Eqs. 6).

\[ SD_{patch} = SD_{mean} - (TWI_{patch} - TWI_{mean}) \times (m \times s_1) \]  

**2.4. Sensitivity analysis and parameterization**

Various hydraulic and physical soil parameters (e.g., \( s_1 \), \( s_2 \), \( sv_1 \), \( sv_2 \), porosity, and porosity decay rate) deter-
mine the daily pattern of streamflow and the amount of water retention. In this study, we conducted sensitivity analysis for these parameters against the streamflow to assess their relative importance in model prediction, and finally, to find the optimal values. Table 1 shows the range of values for sensitivity analysis. Default values and ranges are referred to Dingman (1994) and the RHESSys manual. For this analysis, we utilized the streamflow data from 1982 to 1999 (Jung et al., 2002).

The sensitivity of parameters was assessed for both daily fluctuations of streamflow and peak height. For assessing predicted streamflow accuracy, we used the Nash-Sutcliffe efficiency coefficient (NSec) that is generally applied to assess the predictive power of hydrological models (Nash and Sutcliffe, 1970):

\[
NSec = 1 - \frac{\sum_{i=1}^{T} (Q'_{o,i} - Q'_{m,i})^2}{\sum_{i=1}^{T} (Q'_{o,i} - \bar{Q}_o)^2}
\]

where \(Q'_o\) is the observed discharge; \(Q'_m\), the modeled

Fig. 4. Sensitivity analysis on streamflow.
discharge; \( Q_t \), the discharge at time \( t \); and \( \bar{Q}_o \), average of the observed discharge data. The average of absolute errors for the peak height (assumed that streamflow over 100 mm was a peak) was utilized to explain a tilt of the predicted peak. In the sensitivity analysis, we identified the optimum parameter values while simultaneously changing the parameters. First, parameterization was operated at a rough range, and then was executed again at a more detailed range which was determined by the rough range simulations. The optimum parameter values were determined when the NSEc was the smallest and the average absolute error was near zero.

III. RESULTS AND DISCUSSION

3.1. Sensitivity analysis and parameterization

We analyzed the sensitivity of specific parameterization based on the default value of other parameters. Porosity decay by depth \((P_D)\) and \(s_1\) (for \(m\)) showed the highest sensitivity among the six soil parameters for both streamflow and peak flow (Figs. 4 and 5).
Because PD determines the whole porosity of soil profile, it determines the total capacity for water retention. On the other hand, $s_1$ reflects soil transmissivity by determining the rate of water movement. We confirmed that the input and output of water within the soil were related to the two factors above. It seems that $s_1$ had the highest sensitivity because the horizontal $K_{sat}$ decay parameter determined discharge and redistribution of water in the TOPMODEL algorithm. Similarly, sensitivity analysis on peak flow also identified $s_1$ as the most influential parameter among the six soil parameters (Fig. 5).

Our sensitivity analysis indicated that the patterns of streamflow and peak flow were more sensitive to $s_1$ than any other soil parameters investigated in this study. PD showed secondary importance in determining model predictability. Hence, we applied the parameterization only to both $s_1$ and PD, but other parameters remained at the defaults.

As the result of first parameterization using rough ranges of $s_1$ and PD, $N$Sec showed a maximum value when $s_1$ was at ranges from 0.5 to 2.0 and PD was at ranges from 0.0 to 3.0 (Fig. 6a). Peak flow accuracy was good around $s_1 = 1.0$. Based on the results, more detailed parameterizations at the narrow ranges of $s_1$ and PD were further implemented, resulting in optimum values of $s_1$ ($= 0.8$) and PD ($= 0.2$) (Fig. 6b). Finally, the set of six soil parameters summarized in Table 2 was applied to predict daily streamflow for the study period.

### Table 2. Values of soil parameters used in modeling

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.435</td>
<td>$s_1$(for m)</td>
<td>0.8</td>
</tr>
<tr>
<td>Porosity decay by depth</td>
<td>0.25</td>
<td>$s_2$(for $K_{sat}$)</td>
<td>1</td>
</tr>
<tr>
<td>$K_{sat}$ (m d$^{-1}$)</td>
<td>3</td>
<td>$v_1$(for $m_v$)</td>
<td>10</td>
</tr>
<tr>
<td>$m$ ($K_{sat}$ decay by depth)</td>
<td>0.1</td>
<td>$s_2$(for $K_{sat_v}$)</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2. **Total streamflow**

The reliability of the model prediction was evaluated by comparing predicted and measured annual streamflow at the study catchment. We selected streamflow data for a 10 year period that had no missing data. Results showed that the simulated pattern was very similar to the measured one (Fig. 7). The simulated average annual streamflow (838 mm y$^{-1}$) was well compared with the measured average annual streamflow (843 mm y$^{-1}$) with $R^2$ of 0.90.

The daily variation in the measured streamflow was well predicted by the model simulation (Fig. 8) with $N$Sec of 0.75. Nevertheless, we identified several prob-
problems that need to be improved for more reliable model predictions. For example, (1) the model did not efficiently explain some small peaks and (2) the decrease of streamflow after the peaks was slower than the measured response (Fig. 8c). The former might have been caused by uncertainty in estimating the throughfall and/or insufficient calibration regarding the capability of water retention, while the latter would be related to matters regarding explanation of soil transmissivity and/or the estimation of water consumption by evapotranspiration.

VI. CONCLUSIONS

The measured pattern of daily streamflow was reasonably simulated using RHESSys, and evaluated through intensive sensitivity analysis and parameterization of soil characteristics. Our sensitivity analysis indicated that streamflow and peak flow patterns were more sensitive to the horizontal $K_{sat}$ decay parameter ($s_1$) than any other soil parameters investigated in this study. The porosity decay by depth ($PD$) showed secondary importance in determining model predictability. Some predictive problems were identified in our RHESSys simulation, which
indicated that a slower recession of peak flow and failure for the following small peaks needs to be improved through a more detailed parameterization in future studies. Finally, because our simulation was based on well-described ecological characteristics including LAI and biomass increment, the results could be utilized to simultaneously investigate both carbon and water processes in the catchment.

Together with the uncertainty in model prediction resulting from the errors in model algorithm and parameterization, field data provide an additional uncertainty since inaccurate or insufficient datasets would mislead the parameterization process. For example, the maximum LAI (i.e., one of the key input data) changes from location to location and from year to year and thus the corresponding sensitivity analysis should be performed to quantify the uncertainty associated with such errors. It should be noted also that the calibrated parameters of TOPMODEL (e.g., saturated hydraulic conductivity) may be sensitive to changes in the grid size and/or computation algorithm for topographic wetness index, for example. In such a case, a new calibration process is needed, suggesting that we should carefully consider the scale dependency issue in the model parameterization.

ACKNOWLEDGMENTS

This research was supported by grants (code: 1-8-2) from Sustainable Water Resources Research Center for 21st Century Frontier Research Program, the Eco-Technopia 21 Project of the Ministry of Environment, and BK21 Program of the Ministry of Education and Human Resources Development of Korea. We would also like to thank two anonymous reviewers for helpful comments that improved this paper.

REFERENCES


### Appendix 1: Primary eco-physiological parameters for photosynthesis and tree growth

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>q10</td>
<td>Q10 for maintenance respiration</td>
<td>4.37</td>
<td>dimensionless</td>
<td>T. Hwang (2004)</td>
</tr>
<tr>
<td>per_N</td>
<td>Maintenance respiration per unit nitrogen</td>
<td>0.20</td>
<td>KgC/kgN/yr</td>
<td>default</td>
</tr>
<tr>
<td>gr_perc</td>
<td>Percent of new carbon allocation that is lost to growth respiration</td>
<td>0.25</td>
<td>Range (0 - 1)</td>
<td>default</td>
</tr>
<tr>
<td>flnr</td>
<td>Ratio of leaf nitrogen in Rubisco to leaf nitrogen</td>
<td>0.09</td>
<td>Kg/Kg</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>proj_sla</td>
<td>Specific leaf area</td>
<td>30.80</td>
<td>m²/kg C</td>
<td>E. Kim</td>
</tr>
<tr>
<td>lat_ratio</td>
<td>All-sided LAI : one-sided LAI ratio</td>
<td>2</td>
<td>dimensionless</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>proj_swa</td>
<td>Specific wood area</td>
<td>1.4</td>
<td>1/kg C</td>
<td>default</td>
</tr>
<tr>
<td>leaf_turnover</td>
<td>Annual leaf turnover fraction</td>
<td>1</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>day_leafon</td>
<td>Start of growing season</td>
<td>100</td>
<td>range (1-365)</td>
<td>T. Hwang (2004)</td>
</tr>
<tr>
<td>day_leafoff</td>
<td>Beginning of leaf drop</td>
<td>270</td>
<td>range (1-365)</td>
<td>T. Hwang (2004)</td>
</tr>
<tr>
<td>ndays_expand</td>
<td>Number of days for leaf out period</td>
<td>50</td>
<td># days</td>
<td>default</td>
</tr>
<tr>
<td>ndays_litfall</td>
<td>Number of days for litterfall period</td>
<td>30</td>
<td># days</td>
<td>default</td>
</tr>
<tr>
<td>leaf_en</td>
<td>Carbon : nitrogen ratio of leaves</td>
<td>22.11</td>
<td>KgC/kg N</td>
<td>E. Kim</td>
</tr>
<tr>
<td>leaflitr_en</td>
<td>Carbon : nitrogen ratio of leaf litter after translocation</td>
<td>55</td>
<td>KgC/kg N</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>froot_turnover</td>
<td>Annual fine root turnover fraction</td>
<td>1</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>livewood_turnover</td>
<td>Annual live wood turnover fraction</td>
<td>1</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>mortality</td>
<td>Vegetation loss through mortality</td>
<td>0.01</td>
<td>range (0-1)</td>
<td>default</td>
</tr>
<tr>
<td>froot_en</td>
<td>Carbon : nitrogen ratio for fine roots</td>
<td>51</td>
<td>Kg C/kg N</td>
<td>Y. Kim</td>
</tr>
<tr>
<td>livewood_en</td>
<td>Carbon : nitrogen ratio for live wood (coarse roots + stem wood)</td>
<td>50</td>
<td>Kg C/kg N</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>leaflitr_flab</td>
<td>Leaf litter labile proportion</td>
<td>0.38</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>leaflitr_fcel</td>
<td>Leaf litter cellulose proportion</td>
<td>0.44</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>frootlitr_flab</td>
<td>Fine root litter labile proportion</td>
<td>0.34</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>frootlitr_fcel</td>
<td>Fine root litter cellulose proportion</td>
<td>0.44</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>deadwood_fcel</td>
<td>Dead wood cellulose proportion</td>
<td>0.77</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>deadwood_fdig</td>
<td>Dead wood lignin proportion</td>
<td>0.23</td>
<td>range (0-1)</td>
<td>White. et al. (2000)</td>
</tr>
<tr>
<td>alloc_frootc_leafc</td>
<td>new fine root carbon : new leaf carbon</td>
<td>1.20</td>
<td>dimensionless</td>
<td>B. Lee</td>
</tr>
<tr>
<td>alloc_crootc_stemc</td>
<td>new coarse root carbon : new stem carbon</td>
<td>0.17</td>
<td>dimensionless</td>
<td>B. Lee</td>
</tr>
<tr>
<td>alloc_stemc_leafc</td>
<td>new fine stem carbon : new leaf carbon</td>
<td>1.75</td>
<td>dimensionless</td>
<td>B. Lee</td>
</tr>
<tr>
<td>alloc_livewoodc_woodc</td>
<td>new live wood carbon : new wood carbon</td>
<td>0.54</td>
<td>dimensionless</td>
<td>B. Lee</td>
</tr>
</tbody>
</table>

*Parameters of Eunsook Kim, Bora Lee, Youngil Kim and Taehee Hwang were measured or estimated in this study site, Gwangneung Experimental Forest

### Appendix 2: Primary eco-physiological parameters for evapotranspiration

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>value</th>
<th>Units</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>opt</td>
<td>Optimum air temp. for stomatal conductance</td>
<td>15</td>
<td>°C</td>
<td>default</td>
</tr>
<tr>
<td>tmax</td>
<td>Maximum air temp. for stomatal conductance</td>
<td>40</td>
<td>°C</td>
<td>default</td>
</tr>
<tr>
<td>kcoef</td>
<td>Coefficient of temperature curve for stomatal conductance</td>
<td>0.2</td>
<td>dimensionless</td>
<td>default</td>
</tr>
<tr>
<td>psi_open</td>
<td>Leaf water potential for full stomatal conductance</td>
<td>-0.34</td>
<td>Mpa</td>
<td>White et al. (2000)</td>
</tr>
<tr>
<td>psi_close</td>
<td>Leaf water potential for complete stomatal closure</td>
<td>-2.2</td>
<td>Mpa</td>
<td>White et al. (2000)</td>
</tr>
<tr>
<td>vpdc_open</td>
<td>VPD for full stomatal conductance</td>
<td>1100</td>
<td>Pa</td>
<td>White et al. (2000)</td>
</tr>
<tr>
<td>vpdc_close</td>
<td>VPD for complete stomatal closure</td>
<td>3600</td>
<td>Pa</td>
<td>White et al. (2000)</td>
</tr>
<tr>
<td>gl_sm</td>
<td>Maximum stomatal conductance</td>
<td>0.0046</td>
<td>m/s</td>
<td>Schulze et al. (1994)</td>
</tr>
</tbody>
</table>