Entropy Production of Soil Hydrological Processes and its Maximisation by

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Reply to the comments of anonymous referee 1

We address all of the concerns raised and propose how the manuscript will be altered as a result. The (summarised) reviewer's comments are in italic text, while our responses are formatted as standard text.

1. *The equations in the manuscript contain dot multiplication signs, multiple symbols and derivatives in unusual notation. This causes confusion.*
   - We will remove the dot multiplication signs and replace e.g. $j \cdot X$ with $j\,X$
   - We will replace multiple symbols, e.g. $fnet\Gamma$ with $f_{net,\Gamma}$
   - $dsdT$ in Eq. 11 will be replaced by $\frac{ds}{dT}$
2. *Some parameters are not defined properly.*

   a) *R_V in Eq. 1 is not the ideal gas constant (8.314 J K^{-1} mol^{-1}), thus it is not applicable to air.*

   R_V is not the ideal gas constant, but the specific gas constant of water vapour which has a value of 461.5 J kg^{-1} K^{-1} (see Table A1). By multiplying it with the logarithm of relative humidity (RH) the influence of varying water vapour content of the atmosphere on the potential of atmospheric water vapour μ_{atm} is included. We will replace the sentence after Eq. 2 by "..where $R_{spec,vap}$ is the specific gas constant of water vapour, T_{air} is the temperature of the atmosphere, Φ is the relative humidity of the air..". We will also replace μ_{atm} by $\mu_{boundary\ layer}$ and "atmosphere" by "atmospheric boundary layer" to be more precise.

   b) *The matric potential Ψ_M (Eqs. 2 and 3) is normally expressed in units of metres of liquid head, rather than in J kg^{-1} = m^2 s^{-2}.*

   In the thermodynamic framework, the product of conjugate variables such as mass and its chemical potential has the unit of energy (Joule). Since the combined water potential (matric + gravitational) corresponds to the chemical potential used in thermodynamics, we use the units J kg^{-1}, or m^2 s^{-2}. To clarify this further, we will change the unit of the water potential in the manuscript from m^2 s^{-2} to J kg^{-1}.

   c) *Neither the definition nor the units of Θ_{soil}, the relative water content, are stated.*

   Θ_{soil} is the relative soil water content defined as m^3 extractable water / m^3 soil. Hence, it does not include the irreducible component. The relation to saturation S is: S = Θ_{soil} / $\Theta_{soil,max}$ = $(\theta - \theta_r)/(\theta_s - \theta_r)$ where θ is the total relative water content of the soil in m^3 water / m^3 soil, θ_r is the irreducible component and θ_s is the water content at saturation as defined in van Genuchten [1980]. In our model, θ_r is 0.065 m^3 water / m^3 soil and θ_s is 0.41 m^3 water / m^3 soil, corresponding to the soil type sandy loam [Carsel and Parrish, 1988]. We omitted the parameters θ, θ_r and θ_s in the text for brevity. Since this seems to lead to confusion, we will add the information stated above to the text. We will also adjust the x-axes in Fig. 3 to the range 0 - 0.345 ($= \theta_s$ - θ_r).

d) *The van Genuchten correlation in Eq. 3 does not seem to be correct.*

   Equation 3 in the manuscript is not correct indeed, in front of $\frac{1}{m_{vg}}$ a "-" is missing that was probably lost during the processing of the manuscript. Thus Eq. 3 should be equivalent to the van Genuchten correlation. We will correct this mistake, thank you for picking it up. In the model source code, the correct formulation of Eq. 3 is used, hence our results are not affected.

e) *Why is the sign of the matric potential Ψ_M in Eq. 3 reversed?*

   In this paper, Ψ_M is defined as negative under unsaturated conditions. The (corrected) Equation 3 in combination with the parameter values given in Table A1 reflects this. The reason for this definition is the fact, that, the more unsaturated the soil is, the more work has to be performed to extract water from the soil matrix. Hence, the chemical potential decreases with decreasing saturation degree. We will add this point to the text above Eq. 3.

f) *Why was the van Genuchten correlation (Eq. 3) chosen and how would hysteretic effects be accounted for?*

   The van Genuchten correlation is often used in land surface models and was chosen for reasons of simplicity. Accounting for hysteresis would be an interesting extension to the model we use, but it would also mean an increase in model complexity that is not met by other components of the model and therefore lies beyond the scope of this study.

g) *Why is a maximum of 1.0 and the volume fraction of water in the vegetation used in Eq. 4? The fraction should not exceed 1 (as confirmed by Fig. 3).*

   The fraction of water can indeed become greater than one since the vegetation is able to store water in addition to the potential water content of the tissue (e.g. swelling of tree stems). This situation is rather unusual, but has to be considered for reasons of mass balance. The maximum in Eq. 4 was inserted to emphasise the unusual nature of supersaturated vegetation, but this seems to cause confusion and is not completely consistent. Thus, we will remove the maximum. This does not have a significant effect on the results of the model (the output values change less than 0.1 %).

h) *Does Ψ_{PWP} have the same units as Ψ_M, or is it a piezometric head?*

   Ψ_{PWP} is the value of the matric potential at which plants are not able any more to extract water from the soil (permanent wilting point). Since we express the matric potential in J kg^{-1} or m^2 s^{-2}, Ψ_{PWP} should have the same units. We will change the value in table A1 from 150 m to 1471.5 J kg^{-1} = 150 m * 9.81 m s^{-2} for consistency. We will add a reference for Ψ_{PWP} to the text [Hillel, 1998].

3. *It is not clear whether all processes have been included in Fig. 1.*

   a) *The infiltration flow path (surface water → soil) is not shown in Figure 1, but its entropy production is included.*

   The path surface → soil will be added (see draft Fig. 1).

   b) *One precipitation path (atmosphere → surface water) is shown, but its entropy production is omitted.*

   We did not quantify the entropy production of precipitation because a large part of the dissipation takes place in the free atmosphere, which is not part of the land surface system. Since we have no data about the velocity of raindrops immediately before the impact at the surface, we did not quantify the associated entropy production. The precipitation which arrives at the soil surface is then assumed to be in equilibrium with water at the surface.

   c) *Another precipitation path (atmosphere → river) is not shown and its entropy production is not included. The paths of surface runoff evaporation (surface water → atmosphere) and river evaporation (river → atmosphere) are not shown.*

   The paths atmosphere → river, surface water → atmosphere and river → atmosphere were not shown because they were neglected in the global model (the model does not contain an explicit formulation of the river network).

   d) *The path of bare soil condensation (atmosphere → soil; e.g. dew, frost) is not shown; or is it included in the precipitation?*

   The model only distinguishes between snowfall and rain, where snowfall is calculated from the precipitation and temperature data. The reason for this is the simplicity of the model and the lack of more detailed climate data on a global scale. Water can enter the soil then only as rainwater or snow melt.

   e) *Where bi-directional flow is possible (e.g. root water uptake; baseflow), the entropy production must be positive for both flow directions.*

   Water flow from roots to soil or from the river to the soil would indeed have a positive entropy production, since this could only happen if $\mu_{vegetation} > \mu_{soil}$ or $\mu_{channel} > \mu_{soil}$, respectively. We did not, however, include these flows in the model. Flow from roots to soil is usually associated with hydraulic redistribution, which cannot be described by the simple bucket model used in our study. Flow from the river channel back to the soil does not seem to play a large role on the scale of a model grid cell.

   We will mention the processes described above in the text and state the reasons for their neglect.

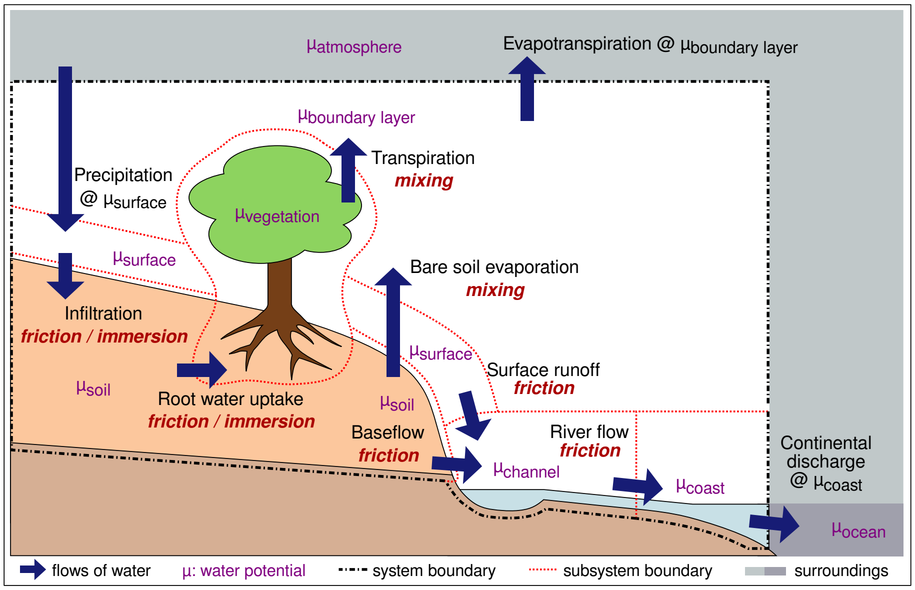

Figure 1: Overview of the flows of water (black text, regular) and the associated entropy producing dissipative processes (red text, italics) quantified in JESSY and SIMBA. The grey shaded areas correspond to the surroundings of the system.

f) *The entropy production of a system is given either by the sum of the entropy productions due to internal flows, or by the sum entropy productions through the external boundary [Ozawa et al., 2001]. It is not permissible to count the entropy productions due to both internal and external flows.*

- *The entropy production of the river path (river → out) is not shown in Fig. 1, but is included in the summation. This is an external flow, so should it be included?*
- *Alternatively, if the authors wish to consider only external flows, they should add only the entropy productions due to the river path (river → outside) and the delivery of humid air to the system (outside → atmosphere).*

The purpose of Fig. 1 is to illustrate the most important entropy producing hydrological processes at the land surface. In the improved Fig. 1, the system "land surface" consists of the subsystems "surface", "soil", "vegetation", "channel network", "coast" and "atmospheric boundary layer". Thus, if the land surface is regarded as the system, all considered entropy production terms are due to internal processes (see draft Fig. 1). Also the entropy production associated with friction during runoff in the channel network is attributed to the land surface. For simplicity we assumed that all the kinetic energy of the runoff has been dissipated when it reaches the ocean. The external entropy exchange flows are not considered in our calculation, which will be made clearer in the text.

4. *The definition of the potential μ_{rain} should be more clearly explained. Also, rain is a flow path, not a compartment; a more appropriate symbol might be $\mu_{surface\ water}$ or $\mu_{overland\ water}$.*

   μ_{rain} will be changed to $\mu_{surface}$ and the respective sentence will be changed to "The potential of free water at the soil surface $\mu_{surface}$ is then set to the gravitational potential at z_s."

5. *Several of the entropy production terms depend upon linearised (Onsager-like) force- flux relations (5), (7), etc, the transport terms of which are used as free parameters (Figure 4). Are there any other free transport parameters, e.g. of transpiration, or other free variables, such as vegetation density?*

   The parameters c_{root} and c_{base} are the only free parameters in the model. The other parameters of the soil model have been set to fixed values (e.g. bucket depth, soil properties). The partitioning of precipitation into runoff and evapotranspiration is most sensitive to the value of c_{root} while the partitioning of runoff into surface runoff and baseflow mainly depends on c_{base}. The other parameters do not have a strong effect on the output of the soil model, hence they were set to the previously calibrated values from Porada et al. [2010]. Since the vegetation model is largely empirical, we used the calibrated parameter values from Porada et al. [2010].

6. *The discretisation scheme used should be explained more clearly. Are each of the entropy production terms in §2.2 calculated for each grid element, or only in total? Are local or global potentials used?*

   For each grid cell all entropy production terms are calculated (root water uptake, baseflow, etc.) using the local values of soil water potential and vegetation potential in each grid cell. Since the parameters of the model are global, however, the grid cells differ only with respect to the climate input data and the height above sea level. This is the reason why the global entropy production of root water uptake and baseflow (the sum of all grid cells) is used for the MEP analysis. We will add the following to the text in sect. 2: "..root water uptake and baseflow is quantified for each grid cell of the model using the local potentials of water (see Figure 1). Soil water storage is represented by a bucket approach. Transpiration by the vegetation and the associated entropy production is calculated in SIMBA, also for each grid cell. An overview of ..". We will add to section 3.2.: " ..they control, namely root water uptake and baseflow. Since all model parameters are global, we maximise the global entropy production of one flow, meaning the sum of all model grid cells, to determine the associated parameter."

7. *Figure 3 is confusing, since it combines two effects; it would be better to separate them.*

   We will separate soil water potential and vegetation water potential in Fig. 3 into two sub-figures (see draft Fig. 3).

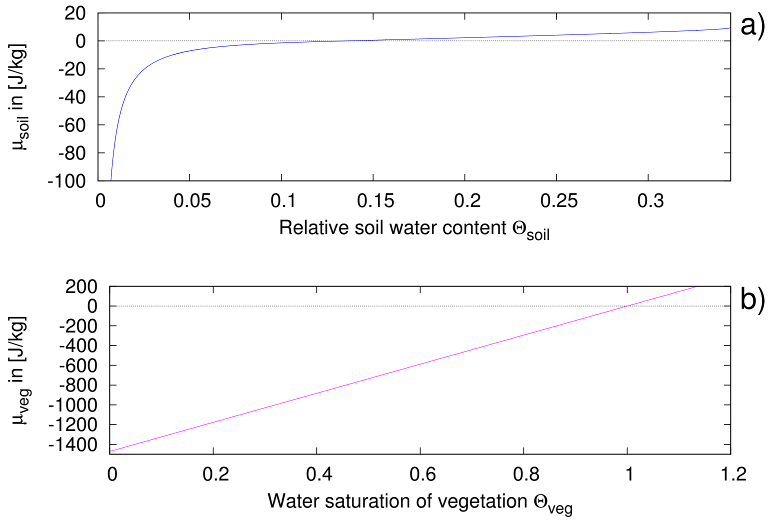

Figure 2: a) Soil water potential μ_{soil} as a function of relative water content of the soil, Θ_{soil} and b) vegetation water potential $\mu_{vegetation}$ as a function of the water saturation of the vegetation, $\Theta_{vegetation}$.

References

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