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Discussions

Interactive comment on "Optimality and inference in hydrology from entropy production considerations: synthetic hillslope numerical experiments" *by* S. J. Kollet

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In the following, comments by Referee#1 are indicated with [R#1] and replies by the author are indicated by [K].

[R#1] The MEP principle is applied to a synthetic hillslope based on a spatially-distributed andd physics-based model. The entropy production is computed. The research question is important and interesting. The methodology is reasonable. I have a few major comments related to the design of the simulation experiments. I hope my comments are useful for the authors to revise the manuscript.

[K] I would like to thank the reviewer for the constructive comments, questions and suggestions, which help to improve the manuscript.

[R#1] Lines 25-27 on Page 5127: Rainfall and other climatic variables (such as temperature and humidity) may be correlated. If rainfall is reduced b by about 30% but other vari- ables are not changed, this may be not realistic. Why not obtain the climatic data from a semi-arid watershed?

[K] It is correct that rainfall and other climatic variables may be correlated. In the simulations, reducing the rainfall was a pragmatic approach in order to facilitate additional simulations in future with increasing rainfall that are consistent with the current setup in order to interrogate the results for different ratios of saturated hydraulic conductivity and rainfall rates Ksat/PCP. I feel this is reasonable given the large uncertainty of hourly rainfall, which may result in similar climate variable combinations, which were used in the simulations and which are reasonable in my opinion. (No rainfall was generated at time steps originally without rainfall.)

[R#1] Related to the comment above: "Runoff out of the domain occurred only for Ksat = 0.0005 (m $h-1$) and S2 and was only 2.2 % of the annual precipitation." (lines 7-8 on page 5129). Even though for the case of runoff (Q)=2.2% of the annual precipitation (R) → the ratio of annual evaporation (E) to precipitation, E/PCP=0.98 → according to Budyko curve, Ep/PCP>3 → potential evaporation Ep>1900 mm since R=637 mm (line 1 on page 5128). I am not sure whether the setting of climatic variables can reach this potential evaporation (temperature is 291 K, line 27 on page 5127). It may be better to constrain the system to the observed pattern or reality when the MEP principle is used for understanding the system.

[K] The climatic variables were obtained from the North American Regional Reanalysis Data Set for the water year 1998/1999 over Oklahoma and were used in previous studies (e.g. Kollet et a., 2008), which resulted in reasonable evapotranspiration checked against Ameriflux tower data. (The calculation of bare soil evaporation, which is relevant for presented study, is addressed in detail below.) Note, that in the aforementioned simulation case, runoff was produced by excess infiltration due to the local, random heterogeneity at the outlet of the hillslope at the "microscopic" scale. Different random realizations may not produce any excess infiltration runoff at all. Because the Budyko concept is valid at the watershed scale, I am not sure about its direct applicability to the hillslope simulations presented here. Yet it is correct that Ep∼1900mm would be high, but not completely unrealistic in my opinion. Large Ep/PCP ratios may also be linked to the thermodynamic equilibrium assumption, which is inherent in the calculation of bare soil evaporation in the simulation explained and discussed below.

In the context of the Budyko concept, I feel it is remarkable that the simulations actually demonstrate that a system can be sustained at dynamic equilibrium along the arid, water limited envelope curve (Ep/PCP > 1) including a saturated zone. This is only possible, because of the non-linearity of variably saturated flow.

[R#1] A further comment based on the above comments, how is evaporation determined? PCP=E for most of the cases. In these cases, the competition between evaporation and runoff is removed. ". . ..entropy production inside equals the net entropy exchange with the outside." (Lines 3-5 on page 2125). How is the power by the evaporation process related to the power computed in this paper? Maximum entropy production (or power) principle is used for a particular flux, and the conductance coefficient is treated as the decision variable. From the system perspective, the entropy production by all the fluxes such as discharge and evaporation may need to be summed (Wang et al., 2015, DOI: 10.1002/2014WR016857). There are two types of competition or tradeoff in the system: 1) flux and gradient for a particularly flux; 2) among different types of fluxes (e.g., evaporation versus runoff). In this paper, some of competitions (e.g., runoff and evaporation) is pre-defined. Some discussions and clarifications will potentially be valuable for the readers.

[K] In the simulations, the variably saturated groundwater-surface water flow model ParFlow (PF) coupled to the land surface model CLM (Common Land Model) was used.

PF calculates variably saturated flow based on Richards equations in a continuum approach, and surface runoff based on a free surface overland flow boundary condition. CLM calculates the water and energy balance i.e. the exchange of moisture and energy (including evaporation from the bare soil, E) with the atmosphere based on the Monin-Obhukov similarity principle. Thus, E is calculated based on

E = roh_atm/raw (q_atm - q_s)

where roh_atm is the density of the atmosphere; raw is an exchange functional explained below; and q_atm and q_s are the atmospheric and soil specific humidities, respectively.

The exchange functional raw is determined by turbulence generated mechanically (based on the logarithmic wind profile) and by buoyancy forces, and is thus a function of the stability of the atmosphere and must be determined iteratively. The atmospheric specific humidity qatm is provided by the atmospheric forcing time series and q_s is calculated using Kelvin's equation, which includes the soil matric potential. The latter constitutes an important coupling of variably saturated subsurface flow with the evaporation and is handled in an operator splitting approach in PF.CLM: at each time step, PF calculates the moisture redistribution based on the evaporative sinks provided by CLM in the top model layer; then the matric potential values are passed to CLM, which in turn are used to calculate the moisture dependent energy fluxes including E. Thus, neither evaporation nor the top boundary condition for subsurface soil moisture redistribution or runoff is pre-defined. They all interact freely based on the coupling, which is key in the entropy production considerations. This is also the reason why decades of spinup simulations need to be performed until the system reaches a dynamic equilibrium. It is important to mention that the application of Kelvin's equation is based on the assumption of thermodynamic equilibrium and may lead to a positive bias in bare soil evaporation estimates, when compared to measurements. This may also be the case here, however, it is not the goal to reproduce measurements, but incorporate important couplings and represent realistically the important degrees of freedom of the subsurface coupled to the land surface.

The power budget is performed for the subsurface, where the power due to evaporation is related to sinks in the top model as explained above. The sinks produce gradients and fluxes toward the top model layer producing power, which were calculated locally using equation 7 through 9 and including the local power budget given by equation 10. Equivalently, precipitation produces gradients and fluxes away from the top model layer producing power, which was calculated in the same way. In that way all the fluxes producing power were summed. At dynamic equilibrium, the global power budget was closed to an increment of 10-12 to 10-14 m2a-1!

While globally (over the entire hillslope) PCP = E, there is still competition between the net flux q (entering along the recharge zone as qinf and leaving along the discharge zone as qex), evaporation, and the dynamic water table. This competition results in the maximization of entropy production in the recharge/discharge zone. It is true that net entropy production over the entire domain is zero given that PCP=E, however there is net entropy export in the recharge zone because of qinf and net entropy import in the discharge zone because of qex.

In addition to the explanation of the summation of all fluxes, it is important to re-emphasize the difference between the useful approach outlined in Wang et al., 2015, DOI: 10.1002/2014WR016857 and the presented study. Wang et al. already work at the macroscopic scale assuming that there exists a representative macroscopic soil chemical potential μs and effective transfer coefficient, ke, for the soil-land surface flux (in their case vegetation flux). In the presented study, a "microscopic" point of few is taken in which the nonlinear fluxes, gradients and interactions with evaporation evolve freely, without any constraint or predefined decision variable. Note that competitions are not predefined. Simulating the actual "microscopic" process the study shows that entropy production maximization occurs at the macroscopic level out of the non-linear processes. In addition, an approach is suggested to arrive at a macroscopic soil chemical potential and effective exchange coefficient as it is used in Wang et al.

[R#1] Lines 11-13 on Page 5128: No flux cross the vertical boundary at x=0? Why not set free discharge at the boundary of x=0 and assuming negligible water depth in the channel?

[K] The hillslope can discharge freely at the top at x=0 based on the free surface overland flow boundary condition and zero depth gradient condition.

[R#1] Line 17 on Page 5128: “In order to identify” Equation (4) on page 5129 and other places: the superscript of net exfiltration/infiltration is changed to (-ex, inf)?

[K] This will be reconciled in the revised manuscript.

References Kollet SJ, RM Maxwell, 2008, Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. Water Resour Res. 44 (2), Doi 10.1029/2007wr006004.

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