Response to Reviewer-2

Review of "*HESS Opinions: Beyond the Long-term Water Balance: Evolving Budyko's Legacy for the Anthropocene towards a Global Synthesis of Land-surface Fluxes under Natural and Human-altered Watersheds*" by *Sankarasubramanian et al.*

The article written by Sankarasubramanian et al., considers the Budyko-framework and the authors explain the framework in a demand-supply setting. They give several examples relating to infiltration, reservoir operations, environmental flows and sensible and latent heat fluxes. The authors argue that formulating especially anthropogenic influences in a demand-supply framework will help explain land-surface responses.

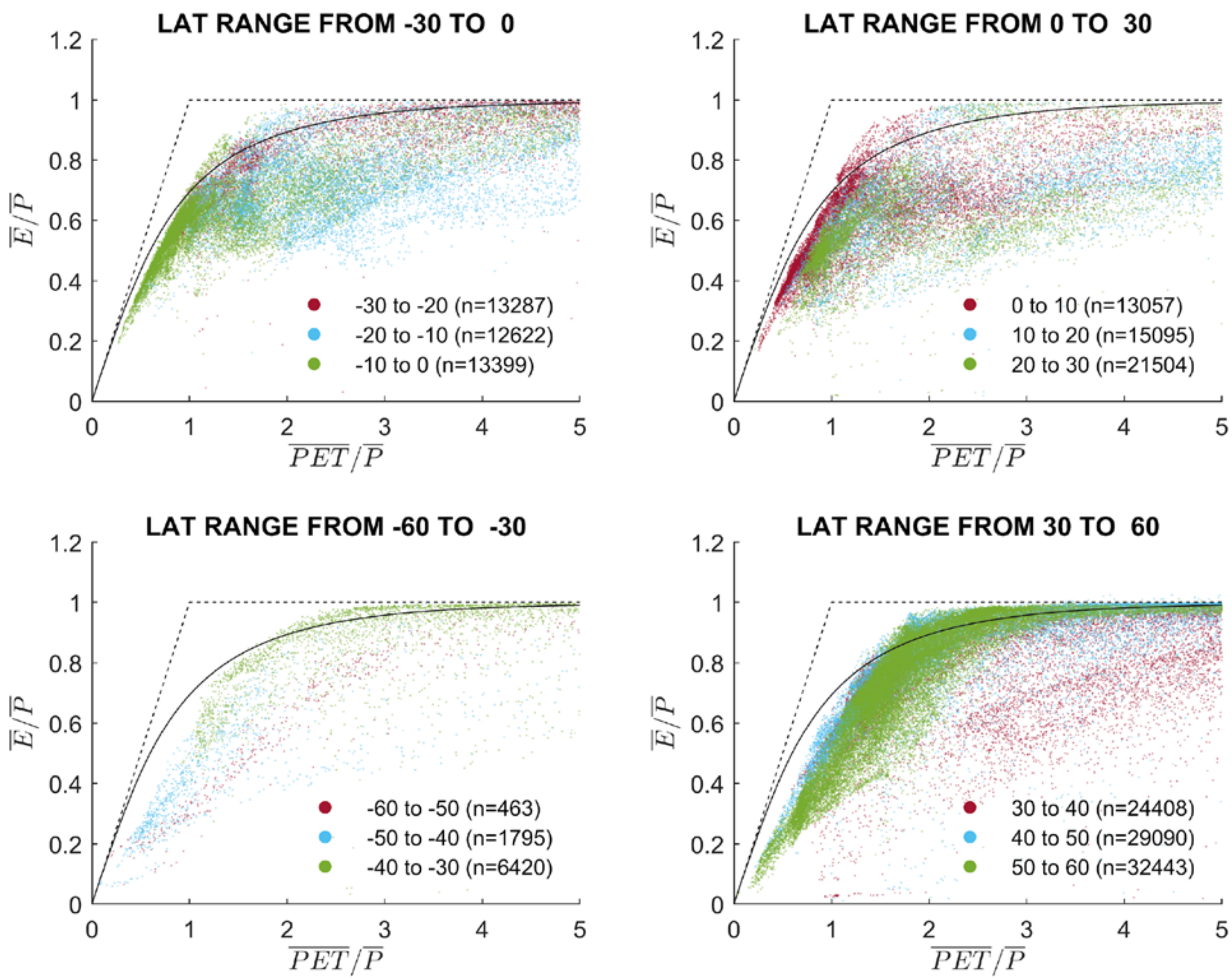
I think the article is very interesting. I fully understand the point of the authors, and I like the idea to use simple demand-supply approaches to understand complex system responses. The article is also well written, and I only have several relatively minor comments.

The proposed method strongly depends on what is defined as demand, and what is defined as supply. For example, in the Budyko-framework one could define the supply in terms of precipitation (i.e. normalize by the precipitation), but also by the potential evaporation. Placing the data in different projections of supply and demand will probably lead to different interpretations, and I wondered if the authors have any suggestions on how to do this systematically.

Response: Thanks for your comments. Our extension of Budyko framework for four different problems, infiltration, hedging, flow alteration and sensible heat flux, provide the context for identifying the "demand" term systematically. The term "demand" provides the upper bound of the "actual" variable if the "supply" variable is unlimited. For instance, in the case of infiltration as "actual", the "demand" is the maximum infiltration capacity, which implies if the "supply" (i.e., rainfall) is unlimited. We identify the demand for each proposed extension in this fashion. We have added the above highlighted definition of demand in the manuscript.

I wonder if the example in Figure 2 is appropriate. The Budyko-framework generally works best for larger basins, whereas here a 0.25 degree resolution is used. More small scale variation might come in, which is often not particularly well-handled in land surface models. For lower values of Ep/P the data also seems to plot always rather far below the analytical curve. I know the authors just want to show an example here, but the spread of the data could also just be explained by model deficiencies in this case. It may better to use observed data, for example the Camels-dataset might be of use for the authors.

Response: The reason we did not use observed data in this Figure is because numerous studies have demonstrated the applicability of long-term Budyko's curves for observed datasets (Sankarasubramanian and Vogel, 2003; Abatzoglu et al., 2017 and others), hence we are not presenting it. Further, presenting the long-term water balance from the GLDAS2 dataset shows the performance of the Budyko curve over various latitudes. To make the latitudinal distribution of fluxes as per the general circulation cells, we have revised Figure 2 with grouped at 10° intervals. The key point from the figure is that there is a lower bound on the evapotranspiration ratio for each aridity index range, which emphasizes the need for other controlling factors such as seasonality of forcings (precipitation and temperature) and soil water holding capacity in influencing the long-term water balance. Further, these low ET ratio happens in the horse latitudes (20-40 N), whereas high ET ratio happens in places with rising circulation cells (0 to 10 N and 50-60N). In the case of the southern hemisphere, organization of circulation cells do not strictly follow latitudinal patterns as the land surface being proximity to the ocean, which makes ET ratio varying substantially from the circulation patterns.



The last example seems a bit off in my view. Generally, "actual" is a realization (or a percentage) of the "demand", varying between 0 and 100%. In this example this is not the case, sensible heat is not a percentage of the latent heat. I think, and the authors mention it themselves on page 12, lines 254-257, putting the framework in terms LE as "actual", Rn as "supply" and potential evaporation as "demand", makes more sense and is more in line with the other examples.

Response: In this example, our "actual" variable of interest is the sensible heat with an intent to understand the difference between urban and its non-urban surroundings. Hence "supply" is the net radiation and "latent heat" is the demand. The formulation suggested in page 12, lines 254-257, is just a reformulation of long-term water balance in energy terms.

Related to this, and actually also my first points, I think it might help to elaborate in the general description of the approach (Budyko Framework Adaptation in Watershed Modelling, p5, line 95) on how to define supply and demand in a consistent way. I my view, the "actual" realization should always be a certain percentage of the "demand", but I'd like to know what the authors propose here.

Response: We have elaborated on how supply and demand should be defined in a given context. The same long-term water balance in Figure 2 could be rewritten to develop asymptotes for minimum runoff by assuming mean annual runoff as the difference between mean annual precipitation and mean annual evapotranspiration. The term “demand” provides the upper bound of the “actual” variable if the “supply” variable is unlimited. It does not have to be a percentage of “actual”. We have added these details with regard to Figure 1.

My last point is merely just a suggestion from my side, but the title does not seem to fully capture the content. At first, I expected (another) extension of the analytical equations in the Budyko framework with a new term accounting for the anthropogenic impact, similar to how some of the cited studies included soil moisture or seasonality in the analytical equations. However, the authors make their argument a lot more general, which I really like, by simply using a demand-supply formulation for complex problems, and from which the Budyko-framework is actually just an example. I think it is important to add at least the supply-demand terms in the title.

Response: We changed the “Budyko’s Legacy” to “Budyko’s Supply-Demand Framework”. Thus, the revised title reads as “HESS Opinions: Beyond the Long-term Water Balance: Evolving Budyko’s Supply-Demand Framework for the Anthropocene towards a Global Synthesis of Land-surface Fluxes under Natural and Human-altered Watersheds”.

Minor comments

P3.L47. Darwinian approach → The Darwinian approach?

P6.L129-130. Suggestion: see the review paper of Wang et al. (2016)

P6.L131-132. Suggestion: this cloud of long term water balance data

P6.L133. Please note, it’s not only energy and soil moisture, the vegetation and thus the transpiration will be affected too.

P9.Eq2. Is the third condition correct? Shouldn’t it be when Smin > Aw – D ?

P10.L207. Not sure if this is true, especially when hedging is applied, when there is storage, more water can theoretically be released than the demand. I would also expect that points would fluctuate around the line, due to delays in a target-feedback-loop, i.e. the actual hedging factor will never be reached exactly and always be slightly bigger or smaller compared to the operational rule. This is different compared to Budyko, where the limits are really physical limits, and not operation based limits.

P11.L235-236. Increased allocation human use → increased allocation for human use

P13.L275-276. For long-term water balance –> for the long-term water balance

Figure 5. I suggest to use a colorscale for the yearly points, so see if there is a temporal trend.

Figure 6. This figure looks like a matlab-screenshot, I would suggest to format the plot a bit nicer.

Response:

P3 L47; P6 L129-130; P6. L131-132 - all corrected as suggested.

P6 L133: We meant here as “moisture” indicating the “precipitation”.

P9. Eq2: Thanks for the nice correction. It should be Smin > Aw-D.

P10, L207: We agree with your point. Linear hedging is a simple operational policy, hence we can expect this line to deviate from the simple case demonstrated it. However, not sure, we follow your point that release can be more than the demand. If we have hydropower, then we tend to release more than the demand for hydropower, without violating the downstream release constraints, as hydropower has the lowest marginal cost to meet the energy demand.

P11 L235-236; P13 L275-276: Both corrected as suggested.

Figure 5: Not sure, we understand this comment. These are annual values not plotted as a time series. We changed the color of the circles - annual releases. Hope this makes it look better.
Figure 6: Fixed as suggested. Here is the plot below: