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Reply on RC1

Isaac Kipkemoi et al.

Author comment on "Climatic expression of rainfall on soil moisture dynamics in drylands" by Isaac Kipkemoi et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-48-AC1, 2021

Reviewer 1

We thank Reviewer#1 for their useful comments. Below in **bold** are our response to the each of the comments.

This paper makes an obvious point, and one that is quite well-known, namely that the temporal resolution of precipitation data can have an important effect on simulated hydrological response.

Although this point may seem obvious to this reviewer, the temporal resolution of rainfall data into hydrological models is not well treated in the literature in the same way spatial resolution has been treated. We believe that both impacts of changing temporal and spatial resolutions must be carefully investigated, especially as hydrological models continue to be employed at much finer spatial scales. There are numerous examples in which rainfall at coarse temporal resolution is used to assess hydrological response in catchments. The issue is more critical to get right in drylands due to the strong sensitivity of rainfall partitioning at that surface to the intensity and duration of driving rainfall events. In this paper, we explore how using precipitation data resolved at different temporal resolutions (hourly, daily, weekly) affects estimates of soil moisture and plant-water availability particularly in dryland regions. This is because datasets currently being used by governments and humanitarian agencies in drylands of developing nations are Globally available (gridded) precipitation data that are typically resolved at daily, weekly, and monthly temporal resolutions. We believe that as a scientific community, it is imperative for us to share accurate information of how the datasets used to drive models that are used for decision making in those regions may not represent inherent hydrological processes of drylands, Hence our broader goals are to investigate the impacts of precipitation on soil water based on the characteristic hydrological processes that occur in drylands (Blöschl and Sivapalan, 1995), including rainfall intermittence, high intensity and short duration storm events, and to identify the critical timescale of precipitation data needed to assess water availability to human society for these vulnerable regions.

Numerical models such as Hydrus can be used to give get insights of natural world processes while achieving computing efficiency and with lower costs.

However, this is an issue that is often overlooked in evaluating issues such as climate change, where the models used to represent future climate scenarios may report data on relatively coarse time scales. Hence a paper that reminds the community of these issues and in particular attempts to quantify the associated effects for drylands is in principle to be welcomed.

We would like to thank Reviewer#1 for highlighting the usefulness of our contribution. Our paper explores an overlooked area in evaluating climate change response reminds the community temporal resolution issues. We think an attempt to systematically quantify effects of rainfall data at temporal scales consistent with the driving hydrology of drylands needs more attention.

There are, however, important limitations of the present paper. The authors seem to have a very limited understanding of the hydrology of the arid systems they are simulating and ignore important effects. A general issue for arid climates such as Walnut Gulch, the case study on which the paper is based, is that summer precipitation is based on thunderstorm rainfall, and is therefore highly localized. This is a major challenge for simulating hydrological response, and one that has been quantified for Walnut Gulch in several publications (e.g. Michaud, J.D. and Sorooshian, S., 1994, Effect of rainfall-sampling errors on simulations of desert flash floods. Water Resour. Res., 30, 10, pp. 2765-2775). This effect is also well described in various books on arid zone hydrology (for example the 2 CUP books, Hydrological Modeling in Arid and Semi-Arid Areas, and Groundwater Modelling in Arid and Semi-Arid areas).

Yes, it is true that rainfall is highly localized at WGEW, a subject that our team has published on (Singer and Michaelides 2017). However, while other studies have emphasized the hydrological response over the entire catchment (e.g, capturing the streamflow signal in the mainstem), our aim here was instead to explore the effects of rainfall resolution on infiltration and AET in a 1D framework. This simple modelling framework, using a well-established and well-tested infiltration model, allowed us to put our focus on the direct impacts of changing rainfall resolution on resulting soil moisture. To accomplish this goal, we have employed two separate analyses. First, we used local rainfall information for a single rainfall gauge (digital gauging station number #82), which is part of the WGEW network and which is co-located with the COSMOS soil moisture probe (http://cosmos.hwr.arizona.edu/Probes/StationDat/010/index.php).The analysis of rainfall at this location and the modelling of soil moisture arising from it, enabled us to directly compare the measured COSMOS soil moisture data to modelled values from Hydrus over the period 2000-2019. We then modified the input rainfall resolution to explore how temporal averaging of input rainfall affects soil moisture.

Next, once we gained confidence of the plausible (hourly) soil moisture series over this historical time period, we explored the potential effects of a systematic changes to the intensity of individual rainstorms over the catchment, without modifying the overall distribution of seasonal rainfall totals. Here, we used the STOchastic Rainstorm Model (STORM) (Singer and Michaelides, 2017; Singer et al., 2018), which explicitly simulates storm events at high spatial and temporal resolution. We used output from this stochastic rainstorm model averaged at hourly resolution and over an area of 15 km^2, which represents the contribution of 15 simulated rainfall locations on a 1-km grid. The purpose of the spatial averaging of STORM output over 10 simulations each of 20 years, was to develop a robust characterization of rainfall inputs to Hydrus to explore the effects of systematic changes to rainfall distributions. To benchmark the effect of these changes to rainfall intensity, we have also simulated stochastic rainfall under

current climate conditions ('historical'). Based on the apparent confusion, we will clarify these points in the manuscript.

A major problem therefore arises when grid-square averaged precipitation from a relatively coarse spatial resolution climate model is used. The effects of spatial smoothing of thunderstorm precipitation will bias the simulations in similar ways to temporal smoothing and is likely to be at least as important an issue. This is not mentioned, let alone addressed, in the current paper. In fact, the paper is quite unclear about its treatment of spatial precipitation. line 213 states that an ensemble average of precipitation from 15 grid locations was used, but the details are not specified, and it is unclear why this approach was used, since the soil moisture simulations seem to be a single site and 1D.

We thank reviewer#1 for raising this issue. We have provided more detail in the response above about rainfall inputs under our climate change scenarios and have updated the text to reflect these points. The most critical point to highlight here is that any stochastic model (representing processes that vary in space and time) may yield biased results for a particular location (based on the simulated expression of rainstorm areas, etc), so it is important to spatially average the results over an area around the site of interest. Ultimately, we want to point out that STORM preserves the inherent intensity characteristics during individual rainstorms, rainfall sequencing, and even the time series of the driving evaporative demand. Additionally, our aim was not necessarily to derive an accurate representation of future climate change on soil moisture at this location, but rather to explore the potential effects of changes in rainfall intensity. Our modelling framework served that purpose.

In Line 213, we will revise the paragraph to read 'we used an ensemble average from 15 rainfall grid locations (Figure 1), covering an area of WGEW where soil moisture has been well monitored. To ensure that our simulations were robust, we used a simulation bounding area around gauge #82 at the Kendall site of ~16 km2. This is made up of 15 rainfall locations, from which we computed an average rainfall as input to HYDRUS. From the resultant dataset we produced 10 realisations for each grid location per climate scenario, each set of data per climate scenario is used to drive Hydrus resulting to an equivalent of 200 years' worth of simulation time. The model soil properties were kept the same for the all the simulations.

It is also well-known that overland flow can be an important process in these areas, and the major mode of runoff generation. This runoff is focussed in the normally dry river channels, and subsequent channel bed infiltration is often a key process for groundwater recharge (and its use by rural communities). However, the conceptual diagram for the HYDRUS model used in the paper (Figure 2) has no representation of overland flow – so it is unclear whether or not this process was represented in the simulations. In addition, intense precipitation can lead to surface crusting (see Morin, J. and Benyamini, Y. ,1977, Rainfall infiltration into bare soils. Water. Resour. Res., 13, 5, 813-817). In the paper, a 1D vertically uniform soil profile is used, and the aggregate soil water response presented in the paper (Fig 6) does not appear to be a particularly good representation of the observations. The 1D assumption may or may not be valid, but more detail of the vertical soil moisture response is needed to convince the reader that the model, on which the whole paper is based, is in fact able to simulate the dynamics of the observed response.

Yes, indeed overland flow, transmission losses into dry channel beds, focused recharge, surface crusting, sediment transport etc. are all important processes in drylands. Our team has published on these dryland processes extensively – including in Walnut Gulch (e.g. Chen et al., 2019; Michaelides et al., 2018; Singer

& Michaelides, 2017; Jaeger et al., 2017; Michaelides & Singer, 2014; Singer & Michaelides, 2014; Michaelides et al., 2012; Michaelides & Martin, 2012; Michaelides et al., 2009 etc.). However, this paper focuses on the 1D vertical distribution of rainfall into the soil profile only – there is no representation of 2D processes of water flow over hillslopes and in channels. We are interested in understanding how soil moisture dynamics vary with rainfalls of different temporal resolutions. Therefore, we are simplifying the representation of this problem in a 1D model of a 1m deep soil profile on a flat surface (similarly to a column experiment performed using typical land surface models). We are using a well-published soil infiltration model (Hydrus – over 3000 publications) to isolate the effect of rainfall and PET on soil moisture dynamics. We believe that the use of Hydrus is justified, for example, over more simplified soil hydrology representation in typical 1D land surface models. Figure 6 demonstrates that we are able to capture the median value of the measured soil moisture response in the top 30cm of the soil profile in the Kendall basin, so we are confident that this model can simulate the broad dynamics of the soil moisture redistribution in this area. There are no long timeseries of soil moisture observations available deeper than 30cm. Also, we want to clarify that this is not a predictive case study. We are using WGEW because of the rich data availability within a dryland site. We are seeking to understand relative differences in soil moisture due to rainfall temporal resolution.

A few specific comments follow:

Abstract: Note that data resolution does not change soil moisture – it does change simulated soil moisture.

We will add '*modelled soil water'* in line 34.

line 46 but is expressed – improper sentence

we will delete '*but'* and add that.

line 88 insert 'and' soil moisture

We will insert *and*

line 132 'we divided reported event precipitation depth (mm) by event duration (min), and then aggregated the resulting set of events into hourly precipitation data' not sure what this means in terms of resolution – presumably nothing sub-hourly?

The highest resolution we use in this study is hourly (as explained in data section 3.2), so yes, we are not using sub-hourly data.

line 193 – note a uniform soil profile was used

We will re-write the sentence as '*e represented the 1D soil profile for the Kendall in Hydrus-1D as a single soil layer with uniform soil properties'*

The soil column properties we are using has uniform soil properties along vertical (z) axis.

line 203 STORM stochastic model used for climate perturbations – method not described

Please refer back to the first two responses above. These will be reflected in the updated manuscript methods.

line 205 what is meant by a high-resolution grid?

1km resolution grid - please refer back to the first two responses above.

Fig 6 – significant differences in the distribution of soil moisture between observed and simulated – these are not mentioned or discussed

There is already a statement about this in the manuscript. In Figure 6 we show boxplots of the modelled (Hydrus) and in situ observed (COSMOS) soil moisture.

The medians of the modelled and observed soil moisture distributions are statistically similar (Mann-Whitney U test, p = 0.5774) while the distributions are statistically different (Kolmogorov-Smirnov statistic, p< 2.2e-16). This is expected and likely due to the nature of multi-year, hourly resolution datasets. Particularly, hourly data from the COSMOS sensor tend to be very noisy than traditional point-scale sensors.

line 213 ensemble average from 15 grid locations was used. Not clear why since soil moisture simulations seem to be a single site and 1D??

Please refer back to the first two responses above that distinguish between our methods for historical analysis of soil moisture versus the future climate change scenarios. These clarifications will be reflected in the updated manuscript methods.

Citations used above:

Chen, S-A., Michaelides, K., Grieve, S.W.D. and Singer, M.B. (2019) Aridity is expressed in river topography globally. Nature 573–577, doi.org/10.1038/s41586-019-1558-8.

Michaelides, K., Hollings, R., Singer, M.B., Nichols, M., Nearing, M. (2018) Spatial and temporal analysis of hillslope-channel coupling and implications for the longitudinal profile in a dryland basin. Earth Surface Processes and Landforms doi:10.1002/esp.4340

Singer, M.B. and Michaelides, K., (2017) Deciphering the expression of climate change within the Lower Colorado River basin by stochastic simulation of convective rainfall. Environmental Research Letters, 12,104011 doi:10.1088/1748-9326/aa8e50.

Jaeger, K., Sutfin, N., Tooth, S.E., Michaelides, K. and Singer, M.B. (2017) Geomorphology and sediment regimes of intermittent rivers; in Datry, T., Bonada, N., Boulton, A. (eds.), Intermittent Rivers: Ecology and Management, Elsevier.

Singer, M.B. and Michaelides, K. (2014) How is topographic simplicity maintained in ephemeral, dryland channels? Geology, doi:10.1130/G36267.1.

Michaelides, K. and Singer, M.B. (2014) Impact of coarse sediment supply from hillslopes to the channel in runoff-dominated, dryland fluvial systems. Journal of Geophysical Research–Earth Surface, doi:10.1002/2013JF002959, 119 (6) 1205 – 1221.

Michaelides, K., Lister, D., Wainwright, J. and Parsons, A.J. (2012) Linking runoff and erosion dynamics to nutrient fluxes in a degrading dryland landscape. Journal of Geophysical Research-Biogeosciences, doi:10.1029/2012JG002071, 117, G00N15.

Michaelides, K. and Martin, G.J. (2012) Sediment transport by runoff on debris-mantled dryland hillslopes. Journal of Geophysical Research-Earth Surface, doi:10.1029/2012JF002415, 117, F03014.

Michaelides, K., Lister, D., Wainwright, J. and Parsons, A.J. (2009) Vegetation controls on small-scale runoff and erosion dynamics in a degrading dryland environment. Hydrological Processes, doi:10.1002/hyp.7293, 23: 1617 – 1630.