**RC#4**

***Interactive comment on*** **"Modeling the paradoxical evolution of runoff in pastoral Sahel. The case of the Agoufou watershed, Mali"** ***by*** **Laetitia Gal et al.**

Received and published: 27 December 2016

We thank the reviewer for reviewing our manuscript and providing his valuable feedbacks. We have addressed all of his/her comments and discussed them in the following.

The paper deals with the "Sahelian paradox" phenomenon where despite a decrease of the precipitation in the Sahel during the last 50 years, an increase of runoff was observed. The Agoufou catchment (245 $km^2$) is taken as a study case, and the spatially distributed model KINEROS2 used to prioritize the different factors (dune crusting, drainage network development, vegetation changes, modification of soil properties, or a combination of some of these factors) that lead to this paradox.

My first feeling is that the title of the paper does not reflect its real content because the paper remains an application of a model on a catchment. Neither the catchment nor the model was chosen to demonstrate a hypothesis related to the "Sahelian paradox".
Moreover the use of the model to prioritize the factors causing the increase of runoff remains a numerical modelling exercise without any validation using hydrological data. The model can give good results for the bad reasons. Consequently the conclusions of the paper on the main factors causing the "Sahelian paradox" may be correct, but may also be not correct.

We will change the title of the paper according to this comment and comments by the other reviewers. We agree that our conclusions are based on a model, and as such call for future work with other models for instance.
The study site (the Agoufou watershed), has been chosen to address the Sahelian paradox. See below for detailed answers.

My comments concern:

i ) The choice of the studied basin: The paper doesn't justify the basin choice in com- parison to other catchments in the same region. Does the land use change and the consequences on the "Sahelian Paradox" observed on the neighboring catchments. In order to demonstrate (or not) the hypotheses and quantify the role of the different factors which lead to the "Sahelian Paradox", it would be preferable to choose the- catchments with internal stream-gauges and piezometers.

The study site was chosen for several reasons:

This site is instrumented by the SO AMMA-CATCH which allows to have field data (soil moisture, LAI, observed discharge, etc.) in the long term (starting in 1984 for the long-term ecological survey), as well as good field knowledge by co-authors.

Gal et al. (2016) show the spectacular evolution of the volume of water entering the Agoufou lake (outlet of the watershed) over the past 60 years despite the decrease in precipitation. This increase in the ponds level is a very good example of the Sahelian paradox that has also been demonstrated in other Sahelian watersheds in Northern Mali (see Gardelle et al. 2010).

This site is a pastoral catchment area where agricultural activity is almost non-existent and cannot therefore be an explanation for the Sahelian paradox (the land use change hypothesis has been put forward in other places). It is therefore in these areas that the debate is open.

These three main reasons explain the choice of this study site, although it will be certainly interesting to extend the analysis carried out on this study site to other Sahelian watersheds.

An increase of runoff will be accompanied with a modification of the other hydrological processes especially the water table level and extension, and evapotranspiration. However, the paper doesn't deal with these two main hydrological processes due to the lack of data. Consequently, the available data are not sufficient to validate or not a given hypothesis.

Evapotranspiration has been monitored with a network of flux stations (up to 5) deployed over different soil units over 2005-2010 (see Timouk et al. 2009, and more data unpublished). It has also been

modelled with different LSM or SVATS (Grippa et al. 2017 in press, Garcia et al. RSE 2013, Bateni et al., 2014 among others). We propose to add a sentence stating that the expansion of rocky soils, silty layers or iron pan likely yields a slight decrease of evapotranspiration over the watershed, coupled to an increase in lake evaporation. Indeed, over deep sandy soils, evapotranspiration is close to rainfall (95% or more, with some uncertainty due to the eddy covariance technique) whereas is it much lower on pediments (< 50%, Timouk et al. 2009). The change in evapotranspiration however is really small compared to the change in runoff and we prefer not to overemphasize it.
There is ongoing work on the water table, which is not facilitated by the security issues in Northern Mali. Geology in the Gourma is such that water tables are variable is size and depth (completely different from the "Continental Terminal" In Niger for instance). Local people do not report systematic evolution of well levels (note that this may be related to the point that water tables are variable and complex in the Gourma, and are not the main water resource used by people there).
Last, in a system dominated by Hortonian runoff, the main players are not evapotranspiration and water tables but rainfall and land surface (the water table is well below the lake bottom, so that it does not feed the lake).

Bateni, S. M., Entekhabi, D., Margulis, S., Castelli, F., & Kergoat, L. (2014). Coupled estimation of surface heat fluxes and vegetation dynamics from remotely sensed land surface temperature and fraction of photosynthetically active radiation. *Water Resources Research*, *50*(11), 8420-8440.

García, M., Sandholt, I., Ceccato, P., Ridler, M., Mougin, E., Kergoat, L., ... & Domingo, F. (2013). Actual evapotranspiration in drylands derived from in-situ and satellite data: Assessing biophysical constraints. *Remote Sensing of Environment*, *131*, 103-118.

ii) What we learn from data: The paper doesn't present a detailed analysis of the spatio-temporal data and do not discuss the evolution of the components of the water balance. The authors must first discuss what we learn from the data only, and in a second time what is the added value using the model.

The data used for modeling are the hydrodynamic soil parameters are derived from the landscape maps described in this paper. We use measured runoff data (Lake Agoufou water balance), which are detailed in Gal et al. (2016) and we prefer not to duplicate what is already written in this first paper. We will make it clear in the revised manuscript.

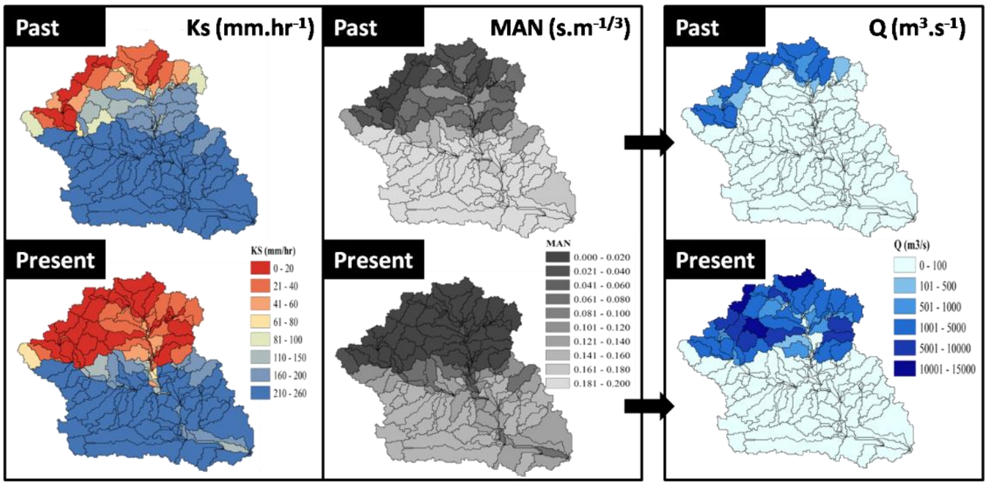
iii) The available data: The main problem is that only "annual" water outflow is available, reconstructed by the author for some years (see Table 1)! Moreover, one rain-gauge is available on the catchment, and data at a fine time step (5 min) are only available for given periods. The lack of analysis of the spatio-temporal structure of rainfall at 5-min time step, and the use of an empirical method for temporal disaggregation is a weak point of the study. Moreover, the paper limits the analysis at the annual water balance and no information is given on flood events characteristics on 5-min time step: evolution from the 50th until now of the rainfall intensities, runoff coefficient, peakflows, lag time, etc. The data are not coherent: a fine DEM resolution (30m) vs annual flow and daily rainfall! I'm not sure that the available hydrological data are sufficient to give responses to the important questions raised in the introduction!

This is an important point, and we think we need to give more explanations and information in the revised paper.

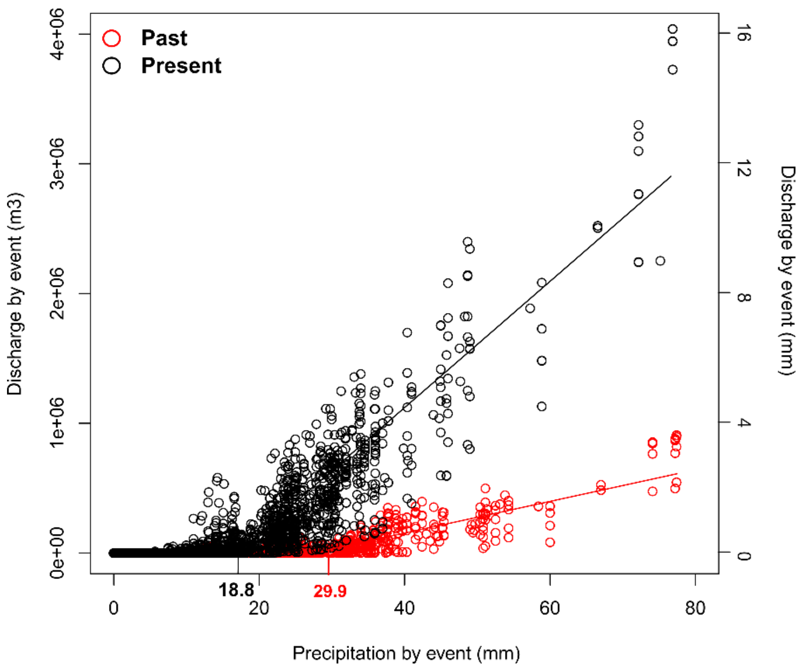
First of all, we propose to add additional figures (one with maps of Ks and MAN for Past and Present, and one figuring runoff versus rainfall for all events of the Past and Present, see below). Thank you for suggesting adding information on the spatial and temporal features of hydrology and changes over time.

Then, we will explain why looking at yearly or 15-year runoff comes from the fact that we want to use 5-min rainfall input. Indeed, given that we need to perform a temporal disaggregation of daily data, which creates noise and variability in the 5-min precipitation forcing, we need to consider ensemble-mean and we need to average over as many events as we can. Using a look-up table of 5-min events preclude from looking at a particular event, since it will not provide the real 5-min intensity for this event, but will on average provide the right distribution of 5-min intensity (see the histogram of intensities, below, for a comparison). That was probably not clear enough in the manuscript. To document the dispersion caused by temporal disaggregation, we have shown the envelopes of the ten ensemble members (Figure 6). We believe it is really important use 5-min rainfall, to be able to implement changes in land surface in a physical way (Hortonian runoff in a climate with short and intense convective precipitation from squall lines)

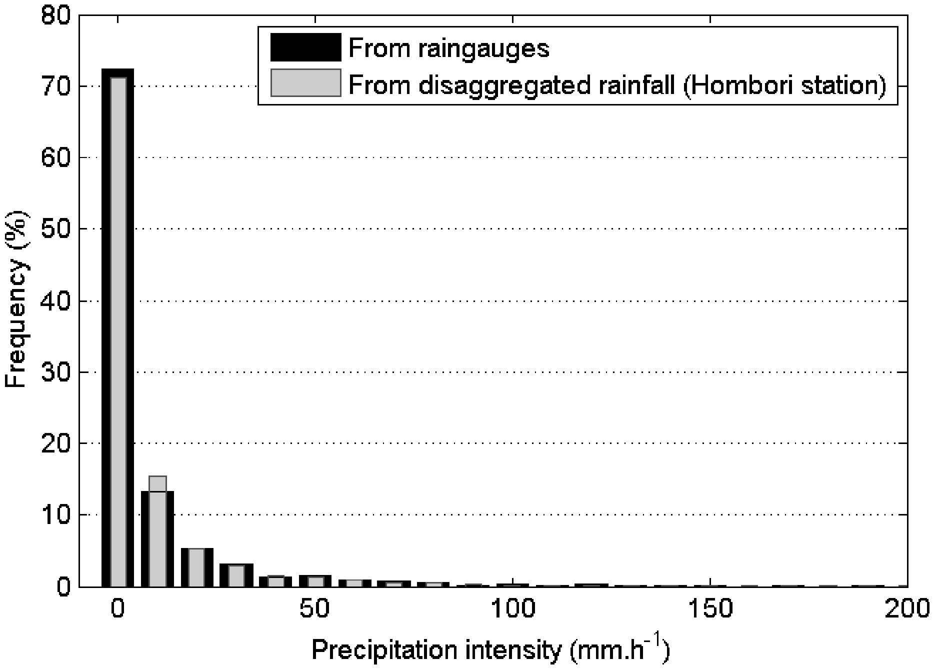
New figures: The figure below shows the impact of the changing landscape on the Manning roughness coefficient and the saturated hydraulic conductivity in the northern part of the watershed. These modifications have led to doubling the contributing area.




The second additional figure represents discharge for all events as a function of event precipitation amount. Two conclusions can be drawn from this figure: 1) for the same precipitation amount, we have twice as much discharge for the present case. 2) For the present period, rainfall events of 18.8 mm and larger average contribute to the discharge whereas in the past rain events larger than 30 mm were required.



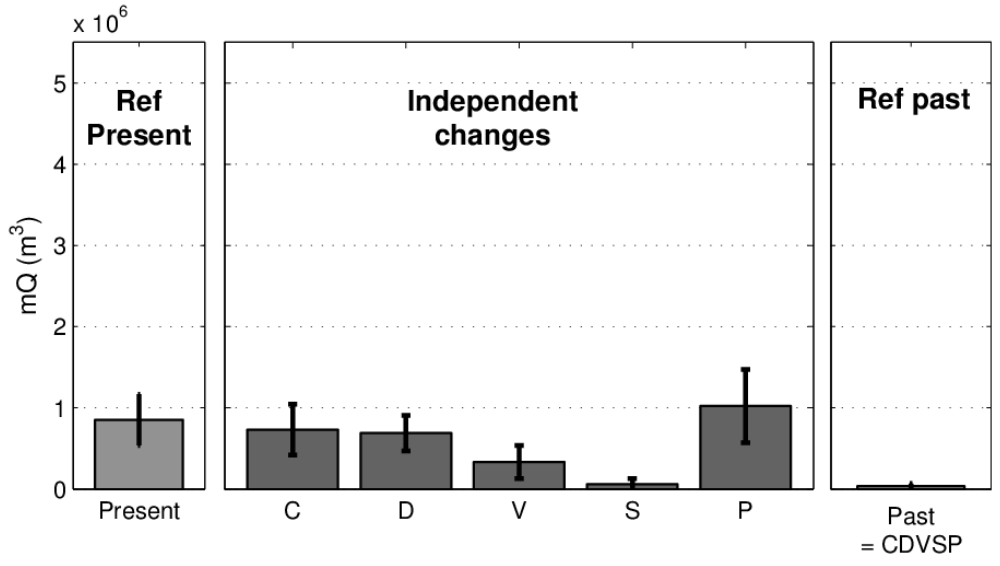
Last, the figure below shows a comparison between histogram of rainfall intensity of two different sources of rainfall (disaggregated and 5-min raingauges). There are quite comparable, particularly for the high intensities which are the most important for runoff production.




iv) The uncertainty on data: The authors must discuss the uncertainty on the hydrological data (e.g. spatial distribution of rainfall, the annual runoff reconstructed) and the consequences on modelling results.

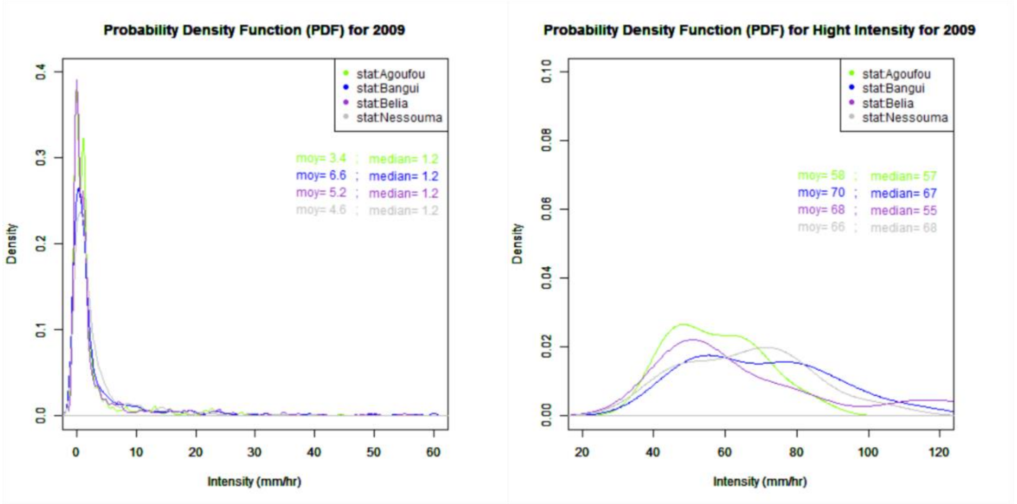
We agree we can provide more information on uncertainty, which is also an important point. For observational data, a full analysis of the uncertainties is detailed in Gal et al., 2016 Journal of Hydrology). We will give more details about this in the revised manuscript.

For the uncertainties on the planes parameters, we will also provide some additional results in the revised manuscript. A sensitivity study has been carried out to highlight the robustness of the model in ranking the factors responsible for the increase of surface runoff. To that end, Ks of all planes was multiplied by 2.5, and MAN by 1.75. This corresponds to the interval given by Casenave and Valentin (1989) for many Sahelian soils. Both changes (Ks and MAN) tend to decrease runoff, therefore the combination of KS and MAN decrease total runoff by a factor of 3.




Ranking and impact of the different changes observed over time are similar to what is found with the original planes parameters.

Last point: Uncertainty due to the use of homogeneous rainfall (one station used): This is an important point. The figure below shows an example of the rainfall PDF derived for different AMMA-CATCH stations for an average precipitation year. Similar rainfall intensity distributions are observed for the different stations, especially for intense precipitation, which contributes to runoff.




To further investigate the question, we had also looked at the cloud top temperature derived by MSG remote sensing data, during this year. This analysis allowed us to conclude that the rainfall cells in the area are generally larger than the watershed area (the contributing part is located to the north of the catchment. Therefore, only one third of the watershed is concerned.) The analysis of remote sensing data revealed an average time lag of 15 minutes between the east and west of the watershed (squall lines usually propagate westward in the Sahel). We agree that this could have a notable effect on runoff. In our simulation setup, the impact of a time lag would only affect the timing of water flow entering channels, given that planes are too small to be affected by the rainfall spatial variability. Thus, flows in channel would be impacted (in fact peak flow should be decreased and flow duration increased, leading to increased infiltration in channels). Such an effect however is compensated for by channel calibration. In addition, even if the absolute runoff values would be different in the case of heterogeneous rainfall, there is no obvious reason that this would change over time and impact the difference between the past and present case runoff, which is the main focus of the paper.

v) The choice of the hydrological model: The spatially distributed model KINEROS2 is used without any justification. I'm not sure that this model is the most appropriate for the available data (only one rain-gauge, and total annual runoff). The paper doesn't demonstrate that the prioritization of factors causing the “Sahelian paradox” are inde- pendent of the model choice. Comparing different models will give more arguments for the discussion.

A previous study, not detailed here (found in Gal L., 2016, “Modélisation de l'évolution paradoxale de l'hydrologie Sahélienne. Application au basin d'Agoufou”, PhD thesis, Université de Toulouse) based on a literature review was carried out with 20 different hydrological models (global, distributed and semi-distributed) in order to select the model best suited to the zone and the objectives of the study. KINEROS2 was found to be suited for the study purpose.

In addition a model/data intercomparison project, called ALMIP2 for AMMA Land Surface Model Intercomparison phase 2, has been carried out in this area to assess the capability of land surface models (LSMs), vegetation models and hydrological models to describe hydrological processes in this area: 20 different LSMs were analyzed (Grippa et al, in press in JHM, available as early release on line at http://journals.ametsoc.org/doi/pdf/10.1175/JHM-D-16-0170.1 or upon request to M. Grippa). The results highlight the difficulty of models to distinguish between shallow or silty soils generating the runoff ending up in ponds and no-runoff areas, like the sandy deeper soils, which infiltrate all rainfall. LSMs have been found to be too sensitive to rain and not enough to soil properties. We hope that our results will stimulate the scientific community to undertake further studies in different basins and with different models to validate or invalidate our findings. The data are being put on the AMMA-CATCH database in that purpose.

vi) The calibration procedure: an important number of the model parameters were arbitrarily fixed and only two parameters were calibrated. The values of the calibrated parameters will depend on the values chosen for the fixed ones. The authors must justify the choice of the parameters to be calibrated, and discuss how a modification of the fixed parameters will impact the conclusions of the paper.

The calibration approach was probably not clearly explained in the first manuscript.
The plane parameters values were derived from FAO codes and soil texture data from field studies. These parameters have not been adjusted because we want to investigate how their changes impact surface runoff (note that we have performed a sensitivity study that provides robustness to our results). Calibration was performed on channels parameters, which are not well constrained by observations. The calibration mostly show that the runoff simulated over the planes yields observed total watershed runoff with plausible values of channel parameters. This is satisfying, of course, but our results on ranking factors does not depend on the calibration.

vii) The criteria function: Only the “Bias” (Eq 3), at the annual time step, was chosen as a criteria function. The paper doesn't present any simulated hydrographs, neither other values of the criteria function (especially criteria related to peakflows) in order to evaluate the performance of the model. Different criteria functions must be used.

OK. RMSE is added to the Bias in the calibration results. We will include this in the "method" section of the revised article. We cannot use the usual criteria in hydrology (Nash, KGE) because we have little data at the intra-annual scale. We have added also a discharge/rainfall plots with all events (see above)

viii) In order to study the “Sahelian paradox”, it will be interesting to compare the com- ponents of the water balance on a large number of basins (and more especially embed- ded ones). Before undertaken a modelling exercise, an analysis of data is necessary in order to link (or not) the evolution of “hydrological” processes to the evolution of land use.

We completely agree that looking at the water balance of many watersheds is highly desirable. There is now ample evidence for the Sahelian paradox (see review by Descroix et al. 2009, and there is an ongoing review paper, by Descroix et al. also, that will update the state of the art on that subject). We contribute to this scientific question in adding information on pastoral area (no or very few crops), and endorheic areas, as well as on ecohydrology processes (Gardelle et al. 2010, Dardel et al. 2014a, Gal et al. 2016, Sighommou et al. 2012, Gal et al. this study, Descroix et al. in prep). It is not easy however to decipher the drivers of the paradox, since many factors do change over time (hydrology, but also climate, land use, demography, crop management, etc…). We believe modelling is also important in highlighting possible causations and new or possibly overlooked factors, until a clear picture emerges. Of course, the fact that few data exist (even on land use) is an issue. We believe our study points a number of important questions on this debated subject.

**Other comments:**

All comments below will be taken into account in the revised version of the manuscript with the exception of the comment on fig 5 (see below) . Thank you for these suggestions.

- Abstract: please indicate the catchment area in the abstract.

- P3, L11-15: The objectives of the paper are reduced to an application of a model on a given basin, and don't give responses to the main question related to the "Sahelian paradox".

- The title of the paper must be in accordance with the objectives announced.

- Section 2.1 "Study site": The hydrological data 'rainfall, runoff) and the spatial data (land use, soil, geology, DEM, etc.) must be presented in this section and nor as input to the KINEROS2 model. The authors must discuss what we learn from data before undertaking a modelling exercise.

- What is the uncertainty on the delimitation of units on maps (from Table 2) and consequently on the area of each class of land use in space and in time (Table 6)?

- How the drainage network was defined on Figures 3 and 4? How the channel network was interpolated in time between 1956 and 2011?

- The Manning coefficient MAN has a unit ((m^1/3 / s)

- Table 3: How these parameters were fixed? What is the sensitivity of the mode l results of these values are taken different?

- Figure 5: The grid used must be refined?

We believe the accuracy we obtain is sufficient for our objectives. Indeed, given that there is some compensation between MAN and Ks, the different combinations of these two parameters close to the one we retained give quite similar values of runoff at the outlet. (For the present period: $3.3.10^{6}$ $m^{3}$ for Ks = 30 mm.hr-1 and MAN = 0.03 $s.m^{-1/3}$ against 3.6.106 $m^{3}$ for Ks = 40 mm.hr-1 and MAN = 0.02 $s.m^{-1/3}$). Basically, it is interesting to note that the map of planes parameters we use combined with channel values consistent with the literature are able to match observed runoff. The main conclusions of our paper (ranking) are not sensitive to this calibration values (see also the sensitivity test for planes parameters). Literature, that often reports MAN values of about of 0.03 $s.m^{-1/3}$ for Sahelian channels and variable Ks depending on the material being eroded on the basin (here mainly silt and clay).