RC#1

Gal – Modeling the paradoxical evolution of runoff in pastoral Sahel. The case of the Agoufou watershed, Mali

We thank reviewer 1 for reviewing our manuscript and providing valuable feedbacks. We have addressed all of his comments and discuss them below.

General observations

This paper deals with the Sahelian paradox: despite the decline of the annual precipitation, the Sahelian region is paradoxically subject to an increase in runoff associated with an increase of the runoff coefficient. The causes of this phenomenon, commonly known as the "Sahelian paradox", are not yet clear. Based on an event-based and physical-based hydrological model, Kineros2, the authors model the runoff on a small basin located in the Gourma under the Niger River loop. The model allows them to prioritize the different factors that lead to this paradox. The title of their article is moreover incomplete since this last part of prioritization does not appear in the title.

Thank you for the suggestion

We have changed the title accordingly (also suggested by other reviewers).

This question of the Sahelian paradox questioned some researchers but many hypotheses have not been validated.

My first observation concerns the approach: a model is not the reality, a model is only an impoverished image of the reality, even a physical-based model: there is always a process of calibration of parameters to be launched; a model parameter have never a physical meaning. Therefore, we can not rely exclusively on a model, however excellent it may be, to determine all processes involved in rainfall-runoff transformation, and even to prioritize them. Now, this paper gives the impression that the authors seek to validate their knowledge they have of the problematic by means of a model. I preach for my part for incessant back and forth between observation and simulation ... I'm therefore a bit dissatisfied ...

We agree, a model is not the reality. We have changed the manuscript to make clear that explanations are "according to the model" and that the results are subject to uncertainties. We believe that this study, even if model-based, has shed new lights on the Sahelian paradox phenomenon and that it provides an important contribution to the debate on the man-made versus natural causes.

My second observation concerns the very numerous approximations made by the authors: we do not know what are their simulation impacts, because the authors did not discuss the subject. They present mean or median results that ultimately smooth the response of the basin.

We have added 2 figures to document modeling result in more details (maps of MAN, Ks, runoff over the watershed, for the Past and Present cases, as well as Precipitation / Runoff plots for the Past and present cases) which illustrate simulation results and add spatial and temporal information (see specific observations section for the Figures).

There is one point that deserves more detailed explanations: the need to lump events and to look at runoff in a statistical way. It is directly linked to the temporal disaggregation of rainfall. We have physical reasons to use a short time step (namely the importance of Hortonian runoff). For each daily precipitation amount, we use ten events with a 5-min resolution. Since they are taken from a 5-min look-up-table, it ensures that on average, we have a good distribution of 5-min intensities (see the figure included on the response to Technical Comment p. 6, below). At the scale of a single event, though, we have no guarantees that the 5-min intensities correspond to the reality. For this reason, we look at annual means and 15 years averages (which are based on a large number of events, so that the statistical distribution makes sense). We also show the variability induced by temporal disaggregation and seasonal results, as an illustration (grey envelops in Figure 6). We have explained that in more detail in the revised manuscript.

However, I congratulate the authors for all the data that they were able to collect and process (it is not simple in these environments) and which was the basis of this work.

Thank you for this remark. We agree that important scientific questions arise in less observed areas.

Specific observations

The study material is very simple: a single watershed, which does not make it possible to give a universal character to the results obtained.

Due to the limited data availability, no studies of this kind have been carried out up to now in pastoral areas of the Sahel, which makes our study original. The Agoufou watershed is a great case study given the unique long-term environmental monitoring, thanks to the AMMA-CATCH observatory and older programs, starting in the 1980s-90s (Boudet, 1972; Hiernaux and Turner, 1996). The watershed displays a spectacular increase in runoff, which has been quantified in a previous study (see Gal et al., 2016).

In addition, the strong evolution of surface water observed at Agoufou has also been observed in the Gourma region (91 lakes, Gardelle et al, 2010) and elsewhere in the Sahel (Niger and Mauritania, see Gal et al., 2016).

We believe that the mechanisms highlighted here for the Agoufou basin may be at play in other regions of pastoral Sahel. Moreover we cannot exclude that these mechanisms may also play a role in other areas where land use change was considered the major cause for the observed hydrological changes. This of course calls for additional studies.

We have explained in the revised section "study area" the reasons for this choice, which also responds to comments by other reviewers

Boudet, G., 1972. Désertification de l'Afrique tropicale sèche. Adansonia 12, 505–524.

Hiernaux, P., Turner, M.D., 1996. The effect of clipping on growth and nutrient uptake of Sahelian annual rangelands. J. Appl. Ecol. 33, 387–399. doi:10.2307/2404760

I would appreciate that the authors use at least one other model and compare the results of these different models and compare them to their observations and their knowledge of the terrain.

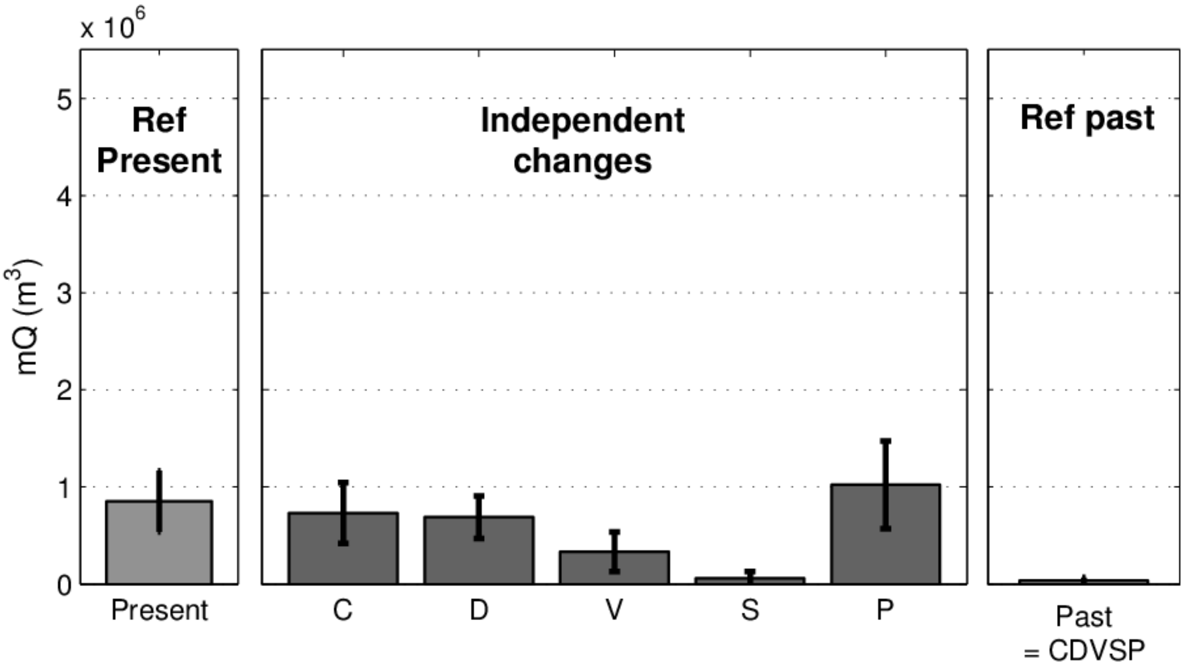
A previous study, not detailed here (found in Gal L., 2016, "Modélisation de l'évolution paradoxale de l'hydrologie Sahélienne. Application au basin d'Agoufou", PhD thesis, Université de Toulouse) based on a literature review was carried out with 20 different hydrological models (global, distributed 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.

Please, give ranges of uncertainties of your treatments/process

For observational data, the uncertainties are detailed in Gal et al. (2016) and have been recalled in the revised manuscript.

For the uncertainties on the planes parameters, we have provided 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. The ranking of the different factors is however the same as with the original planes parameter. This test illustrates the robustness of the results.



I'm not native-english, so I cannot evaluate the quality of the English.

Technical observations

Page 3, lines 30 and after : It also means that as a result of important rainfall events, these ponds may be temporarily interconnected for a more or less long period. Is this type of interconnections possible at Agoufou pond?

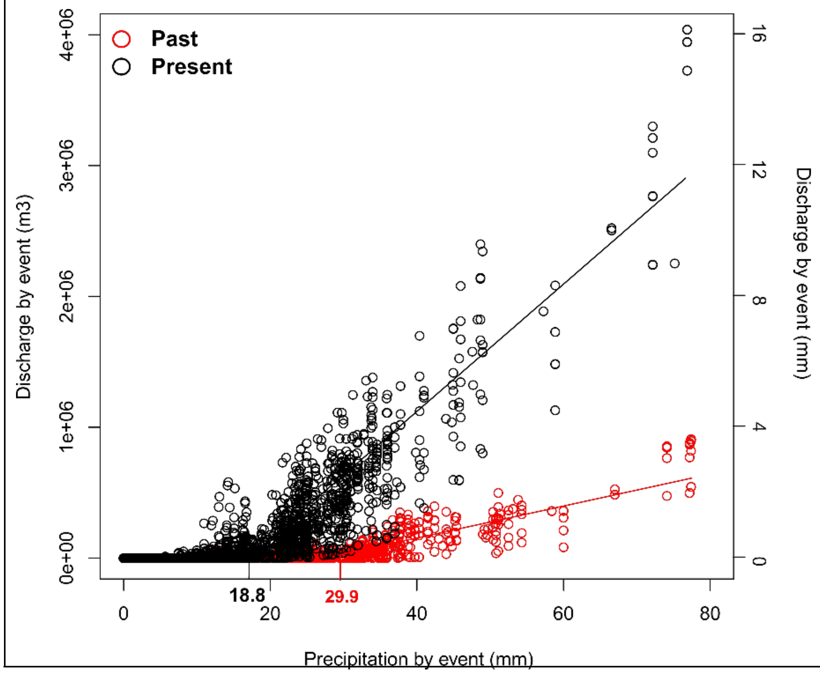
According to the satellite images and regular field survey, no visible connection between the Agoufou lake and the eastern pond has been observed during the whole study period. However, with the dramatic increase in the surface water and precipitation recovery, it is possible that in the future these two lakes will be connected.

Page 4, lines 18 and after: the problem of such a model (event-based model) is to fix the initial conditions for each simulation: how do you proceed?

This is explained later in the article (page 7 line 1 and 30). The initial properties of the soil have to be prescribed to run KINEROS2. We have calculated the time required for the top soil to return to an initial state (dry soil over the first few centimeters) using soil moisture profiles available for different soils via the AMMA-CATCH observatory (described by de Rosnay et al., 2009). This time is rather short (of the order of 48h, depending on soil type) and it is used to separate the different rainfall events. This justifies to reset the soil moisture to initial condition before each event, especially in an area where Hortonian runoff dominates.

Page 5, “Precipitation and meteorological data…”: you need to more detailed your data. Some analyses are needed

We have added the location of the Hombori station in the revised Figure 1 and we give the time scales of the field data (15 minutes for meteorological data used for the STEP model input). In addition, we have added the references to Guichard et al. (2009), Frappart et al. (2009), Timouk et al. (2009) and Gal et al. (2016) who have already analyzed and detailed the in-situ data used here. In addition, we have included new figures, one of them figuring runoff/precipitations for all events.

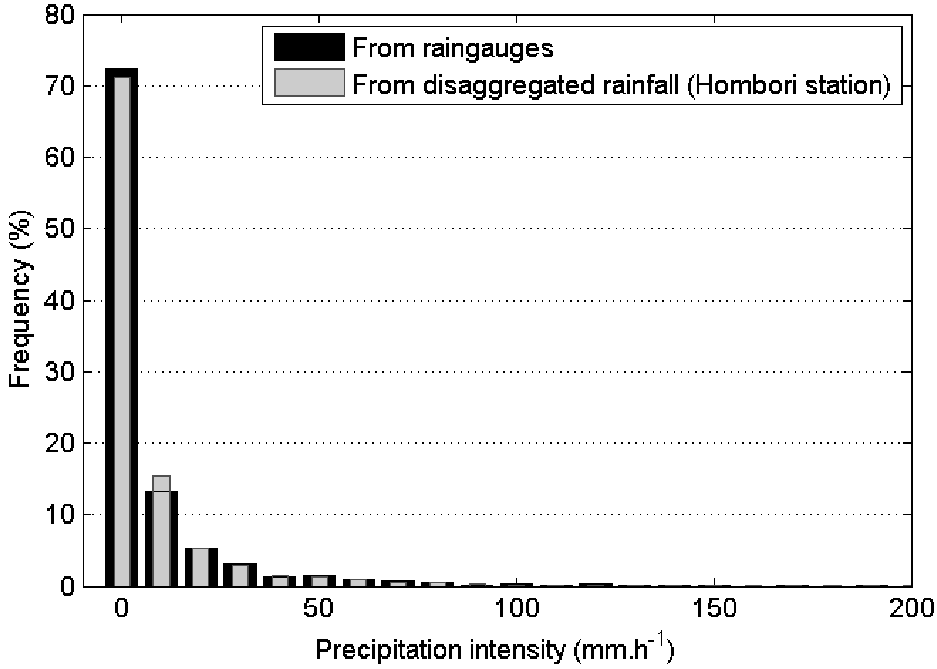


Page 6, “landscape…” : did you discuss of your results with the local population? Did they validate your maps of landscape/.drainage network evolution?

The site has been visited by our team during several field campaigns per year until 2012, and we are working with locals since then (security issues prevent site access for French scientists). One local village chief has been involved in the project since the beginning, and different other persons have been involved in data collection. One of us (Pierre Hiernaux) is extremely familiar with the site, his first measurements in this area started in 1984, and he has leaded the work done on the landscapes map (L. Kergoat and M. Grippa also spent time in Agoufou each year in 2004-2009). We are in regular contact with people living in Hombori and Agoufou, who provide us with valuable information on this region and field data (including regular photographs of the lake, water height, and the vegetation development at the long term monitoring sites).

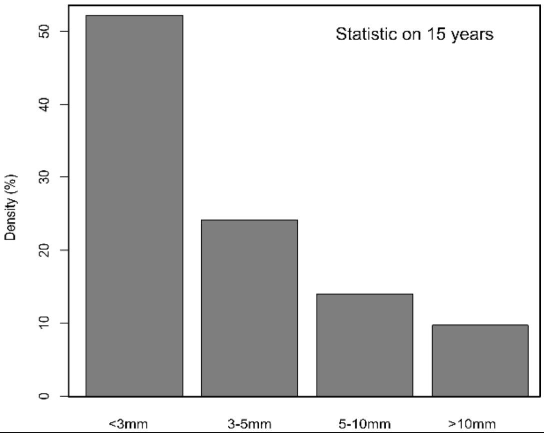
Page 6, “Rainfall…” : astute approach but you have to validate it. That’s why I asked before to more analyse your climatic data.

We have compared the histograms of rainfall intensity (5-min) obtained by the rainfall disaggregation of daily data from the Hombori synop station (figure below, in grey) to 5-minutes data from different rain gauges around the Agoufou watershed available during the 2005-2011 period (black). The figure below shows that the histograms are quite comparable, particularly for the high intensities, which are the most important for runoff production.



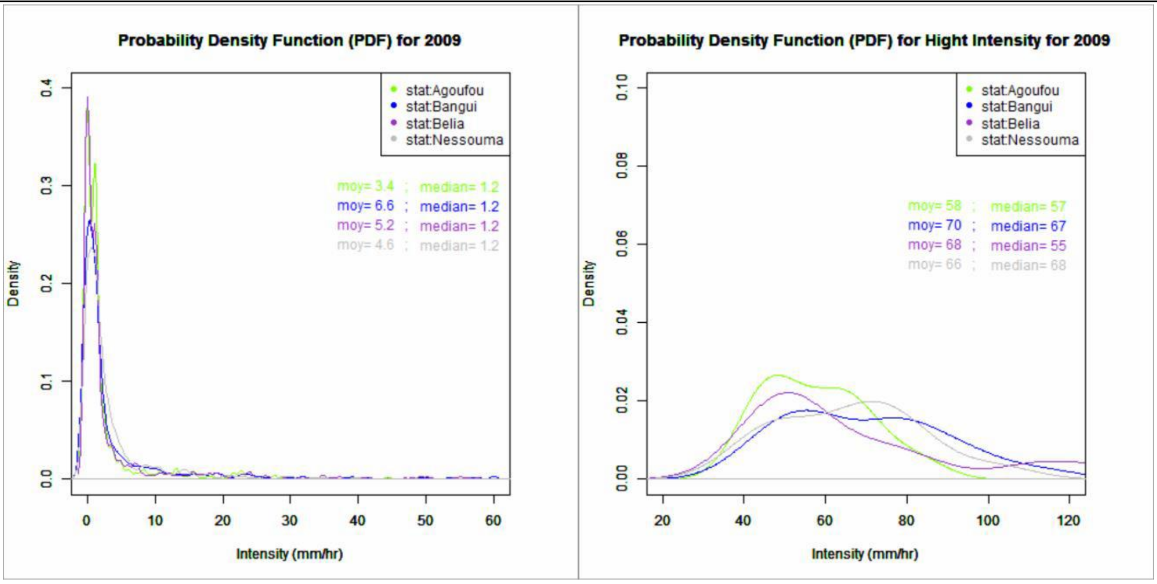
Page 6, lines 35 and after : can we have an idea of how many times you have to widen your intervals?

We have given the statistics corresponding to the figure below in the revised manuscript. Most of the time, intervals are less than 5mm wide (76%).



Page 7, line 4 and after : can't you validate this assumption with the synop station and the stations network of Amma-Catch program?

Indeed AMMA-CATCH stations have been used to address this question. The figure below shows an example of the rainfall PDF derived for different AMMA-CATCH stations for an average precipitation year (There are no others stations than those identified in Fig.1). To further investigate the question, we have 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.



Page 8, "model calibration…" : why don't use an automatic calibration? Why these intervals : you tell later that some values found in the literature are higher? Can we have the dispersion of your ten simulation for an event?

Assessment of the channels parameters is not fully automated and requires a large number of simulations and post-processing. This is why we choose to sample a reasonable interval with a limited number of parameter values. The accuracy obtained appears to be sufficient for our objectives. Indeed, given to the compensation of MAN and Ks, different combinations of these two parameters (in the neighborhood of the retained solution) give close values of runoff at the outlet. So we do not think that too much precision is meaningful. It is interesting to note that, once the plane parameters (Ks, MAN etc.) are prescribed according to local map and survey for texture and built-in FAO soil K2 classification, consistent channel values (compared to the literature) are obtained through the calibration. MAN values of about of 0.03 s.m$^{-1/3}$ are commonly reported for Sahelian channels with Ks being more variable depending on the material being eroded on the basin (here mainly silt and clay).

We do not work at the scale of the event so we did not calibrate at that time scale. However, we also calculated the bias at the intra-annual scale (with all observation data) and we get an average bias of -8% (RMSE = 4.6x10^5), which is also acceptable.

Page 9, "reference …" : it is a too simplistic assumption which have an impact on your results… Isn't it possible to use "interpolated situations"?

We are not sure that we completely understand the question but if it is about providing intermediate steps between the "present" case and the "past" case, it is not possible because we have no data (runoff and land cover evolution) available over this intermediate period. LANDSAT satellite data are rare in the 90ies in this region do to the unavailability of a ground reception station to record acquisitions over West Africa.

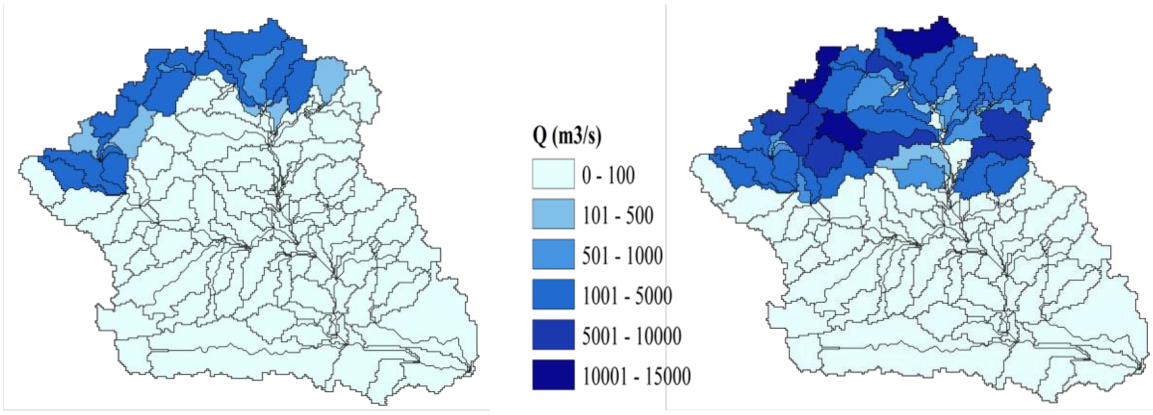
Page 9, "soil land…" : give ranges of the uncertainties of your process. How can you say that in 2011, the western area of the basin contribute to the Agoufou pond? In the Inner Delta of Niger, there is the same phenomenon of interconnected lakes during some strong events; these interconnections are not necessarily permanent ant can disappear for a while; It's certainly the same here. How can you be sure that it does not happen before, between 1960 and 1975?

On the aerial photographs of 1956 it is clear that the western part is not connected to the main network unlike in 2011. This connection is mainly due to an increase and increased concentration of surface runoff given that the heaviest rains before 1956 were not sufficient to connect the western part.

As specified in the article (4.3.2), even if the connection occurred prior to 1975 it should not change the results significantly, since the western part contributes only weakly to the outlet (annual volume contribution = 3.3×10^4 m^3).

The maps below, which have been added to the revised paper, shows the spatial distribution of runoff over the watershed. It highlights the important changes in the northern part of the watershed, which more than doubled the contributing area.

Past (JAS) **Present (JAS)**



Page 13, line 37 : Pierre at al., 2016 is not referenced

Thank you for highlighting this, it has been corrected

Page 14, line 32 : “erreur…” ????

Corrected. Apologies for this error

Page 15, line 34 : what are the “stocking rates”?

It is “Livestock stoking rate” («pression de pâture" in French)

RC#2

Review: Gal et al.

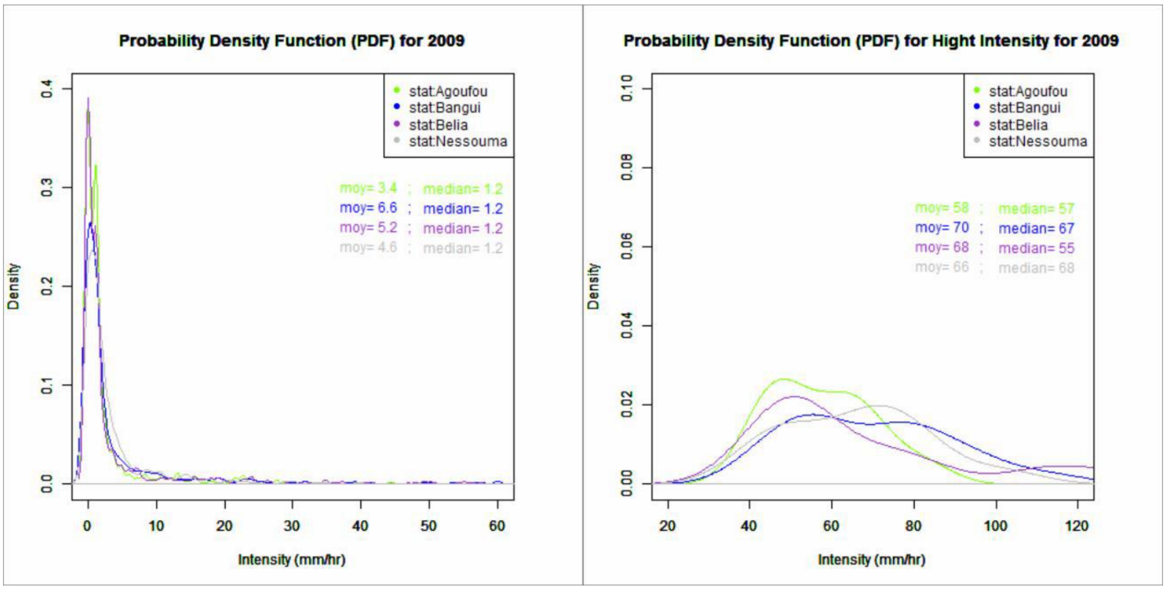
We thank reviewer 2 for reviewing our manuscript and providing valuable feedbacks. We have now addressed all of his/her comments and discuss them in the following.

The paper focuses on a very important topic of runoff generation processes and their changes through time and in identifying the main causes of such changes in an area of sparse data. The objectives and the general approach that was taken in the study to achieve these objectives are scientifically sound and a good and insightful data analysis is presented.

I have however main concerns of the modeling strategy, assumptions and application. They include: a large gap between the model complexity and the data used for its application; sensitivity analyses are essential to justify many of the modeling decisions made, such as which model parameters to calibrate (leaving out probably the most sensitive parameters); the uniform rainfall assumption is very problematic and should be justified; and, model calibration was made against a single number of mean annual runoff volume (although annual volumes estimation do available). See more details below:

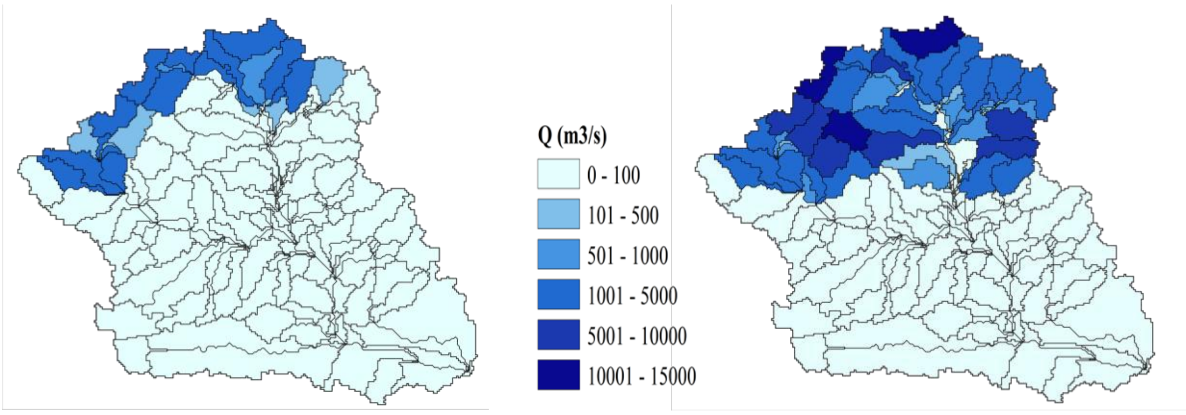
1) The authors rightly present the need of high temporal resolution rainfall and apply a disaggregation procedure. However, in space they assume a uniform distribution of rainfall over the catchment. This assumption is very problematic. Even if the storm cell is more or less at the same size of the basin or somewhat larger, the cell location in space will be often thus that only a partial coverage is achieved. Given the very high sensitivity of runoff to the partial coverage the exclusion of this factor from analysis might add a large uncertainty. Sensitivity analysis of this of catchment runoff to partial storm coverage should at least be examined.

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 (There are no others stations than those identified in Fig.1). 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. This analysis allowed us to conclude that the rainfall cells in the area are generally larger than the watershed area. In addition, the figure below (that have been added to the revised manuscript) shows that the contributing part is located to the north of the watershed. Therefore, only one third of the watershed is concerned.

Past (JAS)	Present (JAS)



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 with the reviewers that this could have a significant effect on the 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 (average 1ha) 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 we agree that the absolute runoff values would be different in the case of heterogeneous rainfall, there is no reason that this would change the difference between the past and present case runoff, which is the main focus of the paper.

2) The change in the channel network density between the two periods was presented by a change in planes aspect ratio rather than the CSA elements. Altering the aspect ratio generates a more or a less elongated catchment shape but the drainage density is changed only a little. Why not to utilize the derived channel network maps and identify for each period its own CSA configuration?

It was probably not clear in the first manuscript, but changing the aspect ratio reproduces exactly the elongation of the channel network (since lateral planes width corresponds to channel length). Changing CSA was considered also but there was a risk of changing planes size, location and properties in an uncontrolled way (changing CSA with DEM and channels network is not straightforward in KINEROS2). That would complicate the interpretation of the changes between the past and present cases. The density factor estimated at 1.3 is not very important at the watershed scale, but when it is computed for the contributing sub-basins, it doubles between the past and the present.

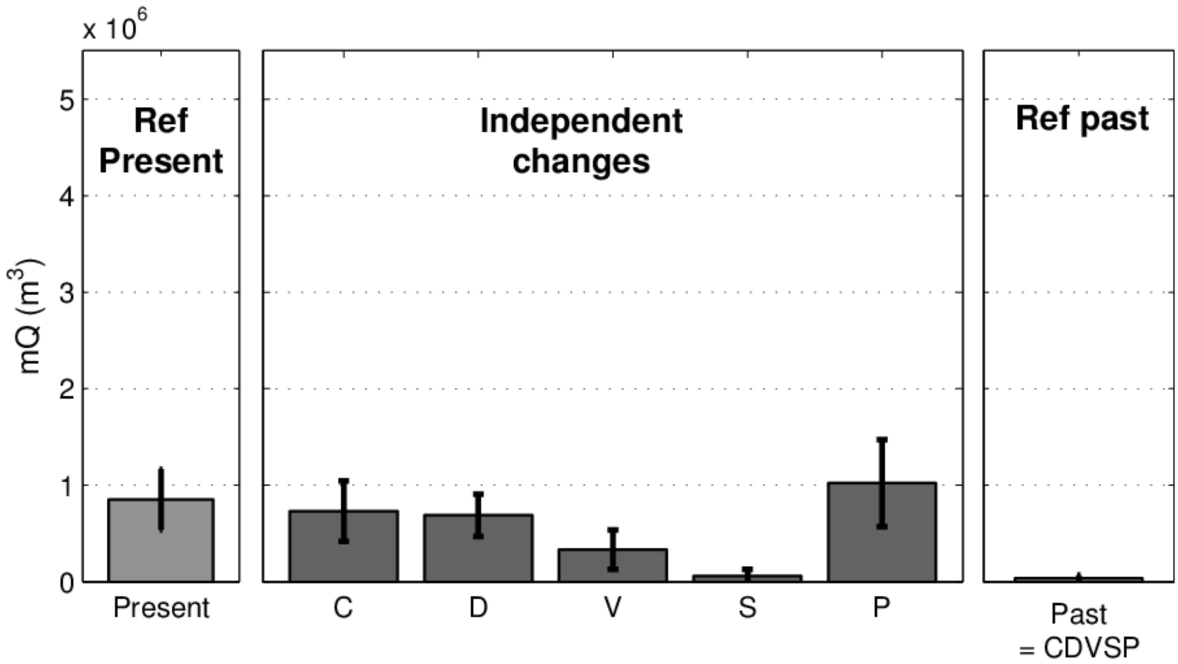
3) Kineros2 has many parameters. The authors have chosen to calibrate the channel Ks and Manning coefficient, while the other parameters were determined using from data and using different functions. This is a very problematic decision – why these parameters were selected for calibration? What do we know about the accuracy of the other model parameters that are not calibrated? There are two necessary steps that are essential to justify the authors decision: 1) sensitivity analysis that will show the parameters that are most important for calibration (i.e., that model output most sensitive to them), 2) for the pre-defined parameters, assess their uncertainty and examine how this is translated into small uncertainty in model output.

4) I believe that total runoff is much more sensitive parameters associated with the infiltration process in the plans, e.g., to plans Ks rather than to channel Manning coefficient and probably to channel Ks. The decision to calibrate the two channel parameters, MAN and Ks is not clear and must be supported.

5) Furthermore, a main impact on annual runoff was found to be the modification of soil properties and vegetation cover, but the model parameters associated with the hydraulic properties of these units were not determined in such a way we have a high certainty in those parameters. Obviously, modeled runoff is very sensitive to these parameters, but they were not calibrated or even examined for their sensitivity.

Based on feedback from other reviewers and reviewer 2, it appears that the objectives of our study and the methodology we employed were not well explained. Therefore, we have better explained this in the revised manuscript.

The objective of this work is to estimate the impact of observed landscape changes on surface runoff. In that purpose, calibrating the plane parameters would enforce a strong constrain on the model, which it is susceptible to mask out or to distort the impact of differences between the past and present case (it is not possible to calibrate each type of plane separately). Our approach was therefore to prescribe the plane parameters from maps of observed landscape changes, using indications on texture (field survey, soil map) and FAO classification soil types. In doing so, we accept that some uncertainty comes from approximated Ks and MAN over planes, but we do not influence the differences between Past and Present.
We fully agree with reviewer 2 that parameters on planes are important in generating runoff. Our paper provides a ranking of the different changes that impacted runoff changes and changes affecting planes parameters come first. We have performed a sensitivity analysis using significantly larger Ks (x2.5) and larger MAN (x1.75) for all planes, which shows that the absolute runoff does change but the ranking of the different scenario does not change, as it is shown by the following figure. This sensitivity test is based on data compiled by Casenave and Valentin (1989) for Sahelian soil, and represents the order of variability of the different types of soils. Both parameters changes decrease the runoff, so the total effect of changing both Ks and MAN that way is a rather strong test (as it can be seen on the total runoff), which provides some robustness to our ranking results.



The calibration of channels parameter plays a minor role, ensuring only that the planes description results in simulated runoff which can match observations with plausible channel parameters. The resolution of the satellite and aerial photographs used to analyze the past and the present does not allow an identification of channel properties (texture) and their possible changes over time. The philosophy adopted for this paper was therefore to calibrate the less known parameters (channels) rather than the most sensitive ones. With the default values of the parameters on the planes, we have obtained, via the calibration, values of MAN and Ks for the channels that are consistent with the literature.
We have explained the calibration approach in more details in the revised manuscript.

6) The calibration strategy seems to me not appropriate. The authors use the bias of the annual runoff as the objective function for calibration; however, Bias does not account for the year by year

variations but integrates all year data into a single value, so possibly a large overestimation of modeled runoff in one year can be compensated by a large underestimation in another year. Instead, an objective function that accounts for the yearly residuals, such as the most popular RMSD objective function is much preferred. It should be emphasized that using the Bias ignores the annual runoff values estimated in the authors previous work and just uses their integration.

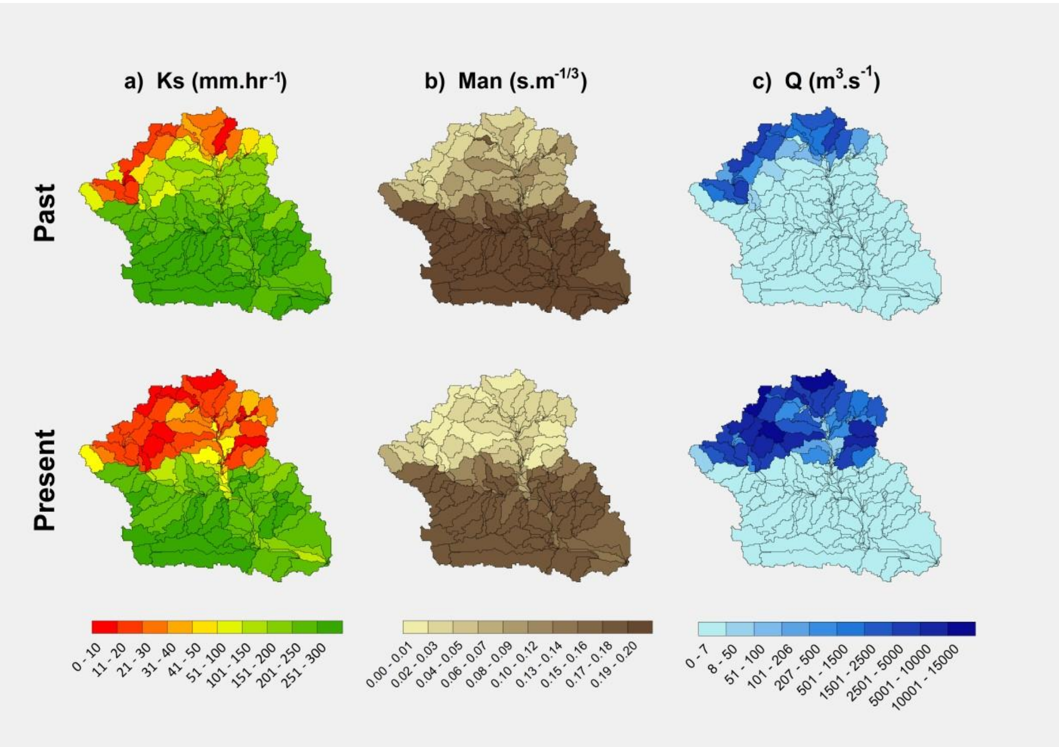
7) Furthermore, a calibration strategy that is based on Bias of runoff volumes, implies that a single number is used for calibration (one data!). This seems not reasonable given the very complex model used and the hard work done to produce very high resolution data.

As explained above, calibration is not critical for the main conclusions of our paper. The RMSE values for the calibration simulations are given in the calibration results.
In addition, we have tested K2 sensitivity to our calibration approach by running the model using other channel parameters pairs (Ks = 40 $mm.hr^{-1}$ and MAN = 0.02 $s.m^{-1/3}$). This yields results that are similar to those obtained using the calibration results (For present period: $3.3.10^6$ m^3 for Ks = 30 $mm.hr^{-1}$ and MAN = 0.03 $s.m^{-1/3}$ against $3.6.10^6$ m^3 for Ks = 40 $mm.hr^{-1}$ and MAN = 0.02 $s.m^{-1/3}$). The RMSE criterion gives Ks = 40 $mm.hr^{-1}$ and MAN = 0.03 $s.m^{-1/3}$. We agree with reviewer 2 that different criteria could have been used, and that RMSE could ameliorate inter-annual variability, but we think that the bias is also relevant for past/present comparison.

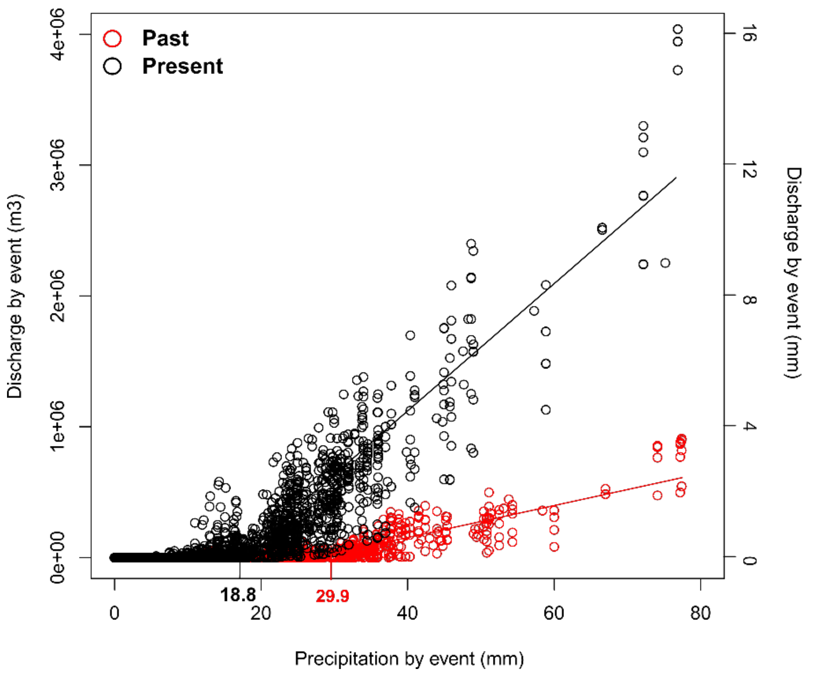
8) The authors utilize a very detailed and high resolution hydrological model (which I am not sure is the most appropriate given the very limited data they have), but they do not really take advantage of the detailed simulations. For example, they could try to understand why the change of soil and vegetation properties increased runoff, for which type of rain events it is more pronounced? Are the change manifested in higher peak discharge or in more streamflow events, etc.

Thank you for the suggestion. We have added figures in the revised manuscript. Two of them show the spatial patterns of the parameters and results and their changes over time, taking advantage of the distributed nature of the model. The other figure is a runoff/precipitation plot, which takes advantage of the event-based simulations.

The first figure shows the impact of the landscape changes between present and past on the Manning roughness coefficient and the saturated hydraulic conductivity for the whole watershed. These modifications have led to a doubling of the contributing part of the watershed.



The second figure represents discharge vs precipitation for all events in the 15 years period in the past and the present. Two main conclusions can be derived from this figure: 1) for the same precipitation intensity, we have twice as much discharge for the Present case. 2) For the present period, rainfall events of 18.8 mm on average, contribute to the discharge whereas in the past rain events of 30 mm are required.



As far as the model choice is concerned, a previous study based on a literature review, (not detailed here but found in Gal 2016, PhD thesis), was carried out on 20 models (global, distributed and semi-distributed) in order to choose the hydrological model best suited to the zone and the objectives of the study. KINEROS2 was found to be the well suited (additional details on this can be found in the response to reviewer 1).

9) As rainfall is so highly variable, conclusions about the effect of its possible change should be done with a caution. For example, the authors state that "The results show that changes in daily precipitation regime do not explain runoff changes between the past and the present." (P. 15, L. 31), but even if such changes do occur in reality it is most likely that they are not statistically detectable due to the high natural variability.

We agree with that comment. We have rewritten this sentence, thanks for the suggestion.

Specific comments

Thank you for the specific comments and suggestions, they have been taken into account in the revised version of the manuscript

1) A climatic description of the area is lacking: mean annual rainfall, potential/actual ET, etc.

OK

2) Only one station is used for rainfall data (and few others are used for the temporal disaggregation); clearly a poor coverage of the catchment, as seen in Figure 1. Have the authors examined the option of remotely sensed precipitation? At least to examine the storm coverage area (which is assumed here to fully cover the catchment.

Yes, we have investigated this issue, which we agree is important. We have also looked at the cloud top temperature, derived by MSG remote sensing data. This analysis allowed us to conclude that the rainfall cells in the area are generally larger than the watershed area (and especially larger than the contributing part, which is located in the northernmost part of the watershed). As detailed in the response to reviewer 1, the calibration of channels parameters mask the effect of rainfall heterogeneity.

3) Assumption of soil recovers its initial conditions in two days – this assumption can be reasonable for arid regions. What about the deep soils in the south?

We have calculated the time required for the soil to return to an initial state (dry soil over the first few centimeters, which controls Hortonian runoff) using soil moisture data available via the AMMA-CATCH observatory described by de Rosnay et al. (2009). This time is rather short (48 h depending on soil type).This justifies to reset the soil moisture to its initial condition after each event. Sandy (deep) soils do not contribute to surface runoff.

4) Add the "absolute value" sign to Eq. 3

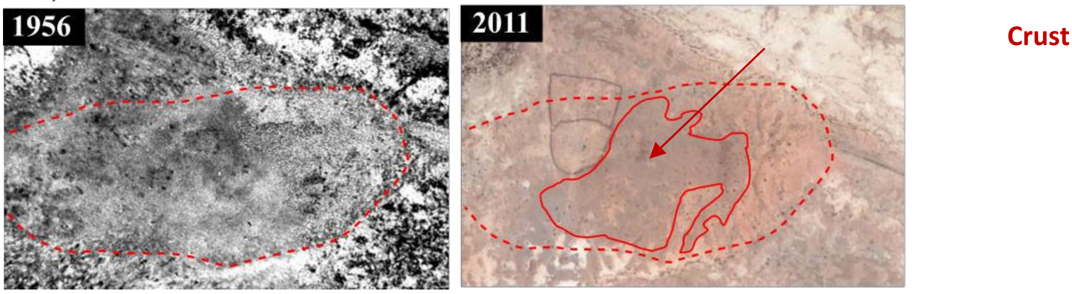
OK. Thank you.

5) The optimization of MAN and KS should be at a higher resolution in my opinion

We do not want to overemphasize the calibration of channels parameters, as it is detailed in response to comment from reviewers 3, 4 and 5. In addition, assessment of the channels parameters is not fully automated and requires a large number of simulations and post-processing. This is why we choose to sample a reasonable interval with a limited number of parameter values. The accuracy we obtain appears to be sufficient for our objectives. Indeed given to the compensation of MAN and Ks, different combination of these two parameters (in the neighborhood of the retained solution) give close values of runoff at the outlet (as mentioned above, comment 7). So we do not think that high precision would be really meaningful.

6) Please clarify how you identified "Isolated dunes (S1) are found at the same location for both periods, but have been eroded and partially encrusted (P. 10).

The images below show that isolated dunes were partially crusted, modifying the hydrodynamic properties of the soil and the growth of the vegetation. This evolution was confirmed by field work (Pierre Hiernaux).



7) Please represent the RMSE value also in percent from the mean (P. 10 L. 22).

We have added runoff values and RMSE values in mm/yr to have a better idea of the rainfall ratio which contribute to the runoff.

8) I recommend to present runoff ratios for each year and to show an example of flood hydrograph.

We have added rainfall/runoff for all events (as well as maps of runoff per plane), which brings information on how the watershed behaves in the Past and Present periods. The observed runoff coefficient have been presented and discussed in Gal et al. 2016, so that we would prefer not to duplicate.

RC#3

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

We thank reviewer 3 for reviewing our manuscript and providing valuable feedbacks. We have addressed all of his/her comments and discuss them in the following.

General comments

This manuscript presents a modelling exercise made for investigating the causes for the so- called 'Sahelian paradox' that consists of a runoff increase in the last decades after the catastrophical drought of the seventies, in spite of a decrease in annual precipitation. The subject is of interest for the HESS readers, uses a known rainfall-runoff and erosion model as well as rainfall input data derived from networks and new information on land cover, soil types and catchment runoff derived from remote sensing and photointerpretation. The paper is mostly well written and its overall formal quality is good.

Nevertheless, the manuscript handles the issues related to temporal and spatial scales as well as parameterisation in too simplistic ways for the results being sufficiently sound to 'explain' or to 'understand' the Sahelian paradox.
Using a 5-minute step event model designed for small agricultural catchments for simulating the annual discharges of a 250 Km^2 basin, assuming that the relationship between daily and 5-minute rainfall intensity did not change on time is not a conventional research approach.

The reasons why we use this kind of model with the data we have (daily precipitation, annual or infrequent runoff) were probably not well explained in the manuscript. We simulate the different hydrological processes at fine spatial and temporal scales. We believe it is necessary given that hydrological processes in the Sahel, as in some other semi-arid areas, are driven by rain events at the sub-hourly time scale (so high time resolution makes sense) and runoff is generated by shallow and impermeable soils occupying a small portion of the landscape (so high spatial resolution also makes sense) by Hortonian runoff. Even if the final objective is to investigate changes between the present and the past 15-year periods, we believe it is critical to use a model that can address this scales. Indeed results from a land surface model intercomparison (Grippa et al, in press in J. of HydroMeteorology, available as early release on line at http://journals.ametsoc.org/doi/pdf/10.1175/JHM-D-16-0170.1 and upon request to M. Grippa) have shown that global land surface models are unable to represent surface hydrology in this area.
In the literature, the size of watersheds studied with the KINEROS2 model varies widely according to the authors. Al-Qurashi et al. (2008) tested the model on a catchment whose area was 734 km² and obtained good results at the annual time scale.
Concerning the rain, we agree that assuming a distribution of rain at 5 minutes which is similar between the present and the past yields some uncertainty. Research on rainfall intensity is currently carried out (including studies by some colleagues of ours) to investigate that, but up to now, no study shows that 5-min intensity has changed between the Past and the Present period.

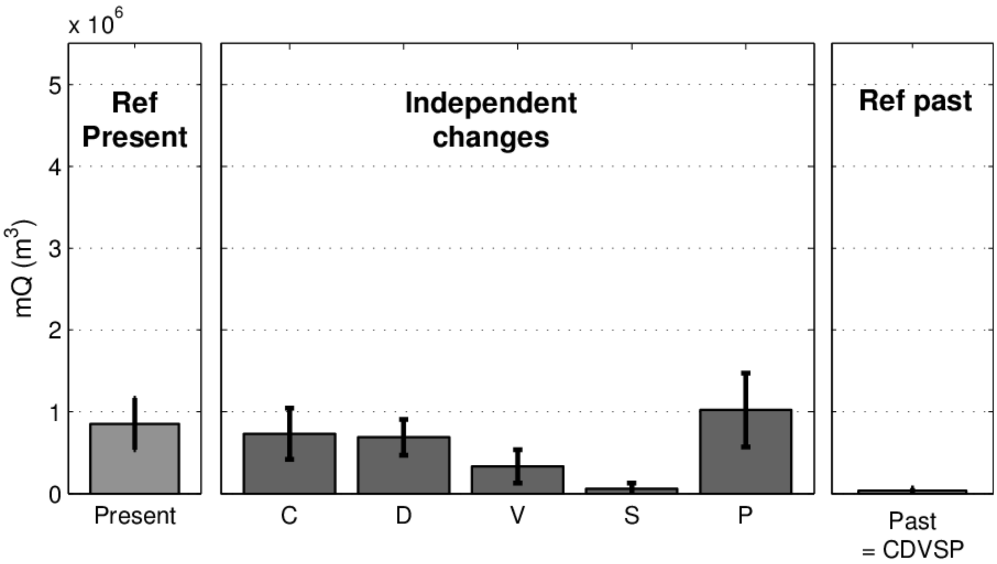
Al-Qurashi, A., McIntyre, N., Wheater, H., Unkrich, C., 2008. Application of the Kineros2 rainfall-runoff model to an arid catchment in Oman. J. Hydrol. 355, 91–105. doi:10.1016/j.jhydrol.2008.03.022

More essentially, as it is well known among the hydrological community that any hydrological model can give good results for the wrong reasons, when the purpose is not to obtain good results but to investigate the reasons, the researcher must be particularly cautious to take into account the likely equifinality of diverse possible parameterizations.

We agree with reviewer 3 statement. Indeed we have carefully selected the hydrological model to use in this study based on its capability of representing the hydrological processes that characterize the study region (model choice is explained in response to reviewer 1 and 2). In addition, we have only calibrated the parameters of the channels to check that the planes parameters produce reasonable runoff (= runoff that fit observation with plausible channels parameters), as explained in response to rev 1 and 2. The overall philosophy was not to calibrate and optimize the most important parameters (planes KS, MAN) and to constrain the model as less as possible. A sensitivity test which multiplies planes KS and MAN by 2.5 and 1.75 leads to the same ranking in terms of Past/Present changes, which provides robustness for our main results. Of course, further studies with different models would be interesting and the data are being put on the AMMA-CATCH database in that purpose.

The paper might be accepted for publication if both the model parameters and results were more investigated. The analysis of the contribution of the diverse factors to the change of the catchment response is a strength of the paper, but it assumes just a 'correct' parameterisation; an uncertainty analysis should be made or, at least, a sensitivity analysis of the model response to parameter variation.

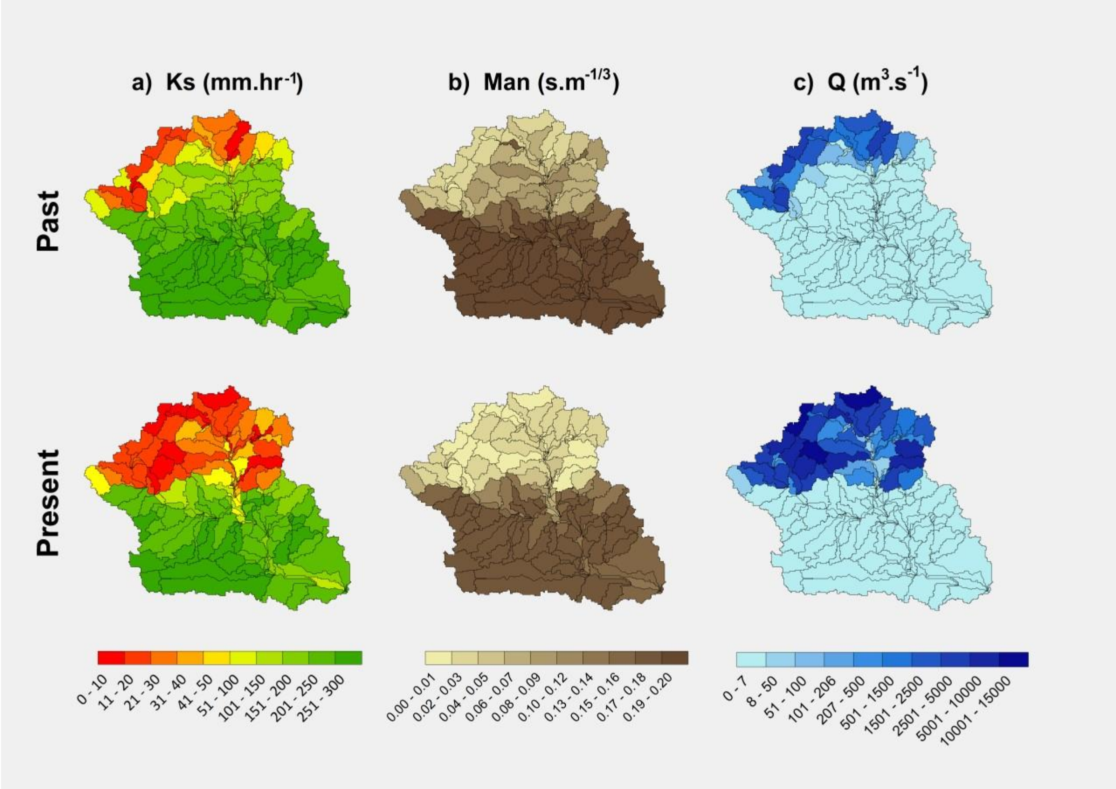
As said above, we have performed a sensitivity analysis using significantly larger Ks (x2.5) and larger MAN (x1.75) for all planes, which shows that the absolute runoff does change but the ranking of the different scenario does not change, as it is shown by the following figure. This sensitivity test is based on data compiled by Cazenave and Valentin (1989) for the Sahel and represents the variability for different types of soils. Both parameters changes decrease the runoff, so the total effect of changing both Ks and MAN that way is a rather strong test (as it can be seen on the total runoff), which provides some robustness to our ranking results.



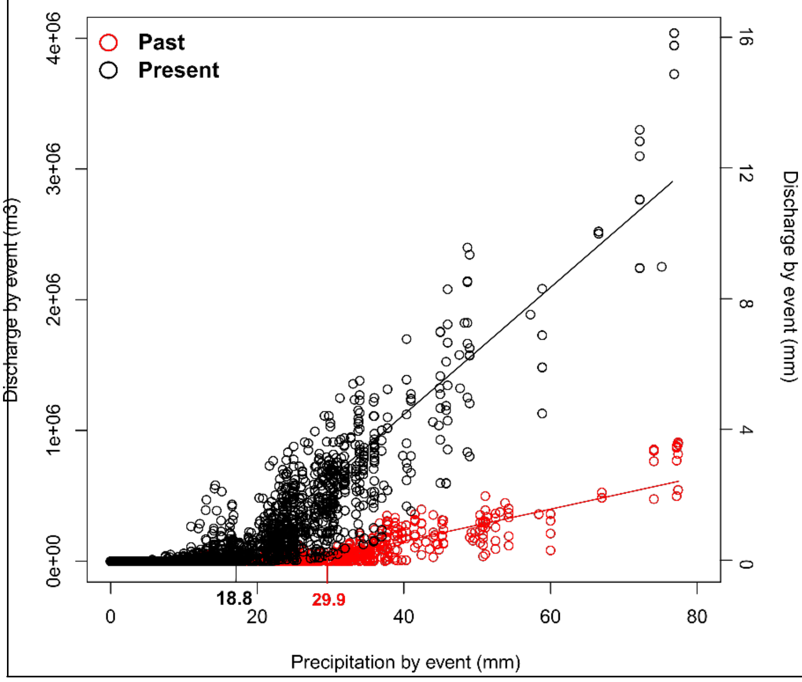
In the same vein, simulations performed with different values of Ks and MAN for the channels give similar results.

Annual catchment discharges should not be the unique focus of model output, but some model results at the event scale (extreme events, annual number of runoff producing events, rainfall threshold values...) and at the landscape unit scale (identification of contribution areas for diverse type of events...) should also be shown and discussed.

Following this suggestion, we have added 2 figures in the revised manuscript, and we agree that they provide very interesting information, thank you for this suggestion. The first figure shows the impact of the landscape changes between present and past on the Manning roughness coefficient and the saturated hydraulic conductivity for the whole watershed. These modifications have led to a doubling of the contributing part of the watershed.



The second figure represents discharge vs precipitation for all events in the 15 years period in the past and the present. Two main conclusions can be derived from this figure: 1) for the same precipitation intensity, we have twice as much discharge for the Present case. 2) For the present period, rainfall events of 18.8 mm on average, contribute to the discharge whereas in the past rain events of 30 mm are required (intercepts of linear fits for non-zero discharges).



Yet, the authors must make a rigorous distinction between model and reality, simulations and observations, as well as more clearly separate drivers, processes and model parameters.

We agree, we have modified our writing in the new version of the manuscript, adding 'according to the model' and similar sentences.

Detailed comments:

Page 1, line 16: KINEROS is not a water balance model but a rainfall-excess runoff model. Water balance, which is the main challenge in the Sahelian paradox, is therefore indirectly simulated, as runoff water is subtracted from infiltration and subsequent evapotranspiration. This is a relevant aspect to be stated in order to assist the understanding of the paper by readers not familiar with KINEROS.

OK. Thanks for the suggestion.

Page 1, line 17: it is necessary to state the catchment area

OK. It have been done.

Page 1, line 23: "shallow soil being eroded and giving place to impervious soils" please rewrite in a less literary way

OK, have been done.

Page 1, line 24: the converse is more rigorous: "The KINEROS-2 model was parameterized in order to simulate these changes in combination or independently".

OK

Page 1, line 26: Catchment flows shown in volume (m^3) cannot be related to rainfall rate and this is not usual in the hydrological literature because volume depends on catchment area, it is more adequate to show them in runoff units (mm per year). Showing only the simulated results is not informative at all (are those simulated with KINEROS2?).

We have added the correspondence between volume in m3 and mm/year and use mm/year when possible as in the rainfall/discharge figure above. (From a water resource point of view volume in m3 is also informative).

Page 1, line 29: "Modification" refers to the action of changing something and should not be used for a natural change. This is unclear that vegetation cover was modified in the parameterisation. Please describe more precisely the modification of parameters made for simulating the landscape changes.

OK

Page 2, Line5: During or after the drought? OK

Page 2, line 25: Reduction of vegetation cover and topsoil crusting are factors of too different nature to be cited together. Reduction of vegetation cover can (directly) decrease rainfall interception and plant transpiration, or decrease the sol protection against raindrop energy, so (indirectly) favour soil crusting. Soil crusting usually decreases infiltration rates and favours rainfall-excess overland flow. Please, describe more precisely the drivers and mechanisms that have been pointed out for explanation of the 'Sahelian paradox'.

OK, thank you for the suggestion.

Page 4, line 2: "and runoff is frequently generated over them."

OK

Page 4, line 21: KINEROS was not designed explicitly for arid and semiarid areas.

Agree, but most of K2 applications concern semi-arid zones so far. The sentence have been changed accordingly.

Page5, lines 18-22. These are not soil and land cover data but just images. OK

Page 6, line 13 (and below): "Erosion surface" seems to refer to a geomorphic unit (land form), but here is not a good denomination for a landscape unit because it is not clear to most readers and it is equivocal with the soil erosion processes. "Pediment" is a geomorphic English term equivalent to the French "glacis" term that could be used instead.

OK. We have changed the text accordingly, thank you.

Page 6, line 30 and subsequent: This is one of the main weak points of the paper, as the method used assumes that there is no change in the fine temporal structure of rainfall events. In the lack of data to improve the approach, some sensitivity exercise should be made to test the role of changing this structure on runoff generation. This may be made using a range of 'ensemble' 5- minutes series with higher, average and lower 5-minute intensity within reasonable bounds.

This is certainly an important topic. However, we have little information so far to provide reasonable bounds for 5-min intensities. There seems to be a change in the frequency of high rainfall events (Frappart et al. 2009, Panthou et al. 2014), starting around 2000. This is a rather weak signal though. To our knowledge, trends for the very scarce 5-min long times series (ex. Niamey station, Léauthaud et al. 2016) have not been evidenced. We feel like such a sensitivity test would be a little bit speculative for this paper and we prefer to stick to the conclusion that daily rainfall regime change (which has been observed with large dataset) does not contribute to increase runoff in our case.

Leauthaud, C., Cappelaere, B., Demarty, J., Guichard, F., Velluet, C., Kergoat, L., ... & Mainassara, I. (2016). A 60-year reconstructed high-resolution local meteorological data set in Central Sahel (1950–2009): evaluation, analysis and application to land surface modelling. International Journal of Climatology.

Page 7, line 19 and subsequent: In fact, there is a terminological confusion in the paper respect to the changes in the drainage network: the changes observed are really changes in the stream channel network; in the old period runoff was too slight or infrequent in the thalwegs to form distinguishable channels that were cut after the drought period (see another comment below). The subsequent paragraph describes how the DEM derived drainage network was adapted to the network observed in 2011, but not clearly how the 'old' network was parameterized.

OK, we agree that additional details are needed here. This has been explained in more details

Page 7, line 34: Thickets

OK, thank you

Page 8, line 1: Low LAI is a reason but high winds favour the evaporation of intercepted rainfall. Check the rainfall interception literature in semiarid areas (e.g. Llorens & Domingo Journal of Hydrology, 2007)

We have been checking the literature before assuming no interception. There are few data for similar biomes and similar climate (strong convective event with strong gusts, low vegetation cover).The nearest case studies are for semi-desert sites or desert sites, for instance the sites documented by Carlyle-Moses, D. E. (2004). Throughfall, stemflow, and canopy interception loss fluxes in a semi-arid Sierra Madre Oriental matorral community. *Journal of Arid Environments*, *58*(2), 181-202. (Review by Llorens and Domingo is mainly for trees, and include 3 bush sites with Mediterranean climate).
Studies in arid/semi-arid environment point to small interception losses (e.g. less than 10%) with high throughfall and significant stemflow.
In our case, the rainfall rates that produce runoff are the highest convective rates, for which interception can be neglected. We agree that interception can occur for instance at the very end of a convective event, when 'stratiform' precipitation sometimes occur, but these do not produce runoff. Also, the area contributing to runoff has an extremely low vegetation cover. Deep soils with important grass cover and scattered trees don't produce runoff, although interception losses are set to zero.
Therefore, we believe it is reasonable to neglect interception when the objective is runoff simulation.
In terms of evaporation during convective events, the high winds (gusts) come with high relative humidity (close to 100%), cold air, and large cloud cover (and the diurnal cycle of convection and squall line produces maximum rainfall from late afternoon to early morning). Information can be found in Frappart et al. 2009, Guichard et al. 2009, Samain et al. 2008, Largeron et al. 2015, for rainfall and associated meteorological data.

Largeron, Y., Guichard, F., Bouniol, D., Couvreux, F., Kergoat, L., & Marticorena, B. (2015). Can we use surface wind fields from meteorological reanalyses for Sahelian dust emission simulations?. *Geophysical Research Letters*, *42*(7), 2490-2499.

Samain, O., Kergoat, L., Hiernaux, P., Guichard, F., Mougin, E., Timouk, F., & Lavenu, F. (2008).

Analysis of the in situ and MODIS albedo variability at multiple timescales in the Sahel. *Journal of Geophysical Research: Atmospheres*, *113*(D14).

Page 9, line 22 and subsequent: In the writing of the following paragraphs there is sometimes confusion between the changes of the extension of the mapped landscape units, the changes of the properties of these units and the related hydrological processes.

OK, this has been rewritten. Thank you.

Page 10, line 9 and subsequent: Please, change the "Erosion surface" term.

OK

Page 10, line 11: "an important erosion of the underlying soil has occurred": do you have evidences of this phenomenon? Where are the eroded soils deposited? "Impervious bare soils have replaced most of these areas": this is not a rigorous description of a landscape change. In all this paragraph there is confusion between changes in the map units, the characteristics of these units and the processes related to these changes (as causes or consequences).

This has been rewritten more clearly. Erosion is both wind driven (particles are exported/imported) and water driven (particles are deposited in ponds and channels) and both processes interact (wind driven particles can be washed out by water erosion for instance, and dry banks can be eroded by the wind).

Page 10, line 15: The development of a drainage network (in fact this seems to mean that new channels are observed in previously unchannelled thalwegs) may be attributed to the increase of overland flow, but not necessarily to the change from sheet runoff to concentrated runoff on the hillslopes, unless new rills and shallow gullies are observed throughout. The entrenchment of channels in semiarid conditions has been attributed to increased runoff or the decay of valley bottom vegetation (e.g. Nogueras et al. Catena 2000 and cited references).

The two factors can play a role even if it is not easy to distinguish between them (an example of changes in the drainage network is shown below)

Runoff concentration was pointed out by several studies carried out in the Sahel also. A typical case is the transformation of a tiger bush (e.g. site 8 of the long term survey, Dardel et al. 2014a), with vegetation bands perpendicular to the flow, which is replaced by bare soil with scattered trees (mostly Acacia ehrenbergiana) that grow along the newly created rills, parallel to the slope. Field survey provide many example of conversion of sheet to concentrated runoff in this area. Of course there is an interplay between increased runoff, concentration, vegetation decay.

Page 11 line 5 and subsequent. This sub-section is not well written. The parameterisation of the channels is not a result. Please, describe changes in precipitation before changes in discharge and use a chronological order of the periods when possible. Reporting discharges in volume is really difficult to follow, please use runoff units (mm/year). Please, state observations before simulations throughout.

This has been done.

Page 11, lines 16-18: this paragraph is unnecessary unless the behaviour of the catchment is better described, as proposed above.

OK

Page 11, line 24: Please, include a sentence recalling that the reference run is the recent period and that changes are evaluated using equation (4).

OK

Page 11, line 26 and subsequent: "... present characteristics except dune crusting ...". "... has two effects on the parameterisation of the land surface ...". "... dune crust on the simulated annual discharge...". Reporting volumes for the sub-basins is confusing, please report percentages of the total runoff and clearly state that these are simulated values for the recent/older periods.

The percentage corresponds to the fraction of dune to be crusting. Its effect on discharge is presented on the result paragraph.

Page 12, lines 3 and subsequent: Please, state the (indirect) effect of the vegetation changes on model parameters, this is to help understanding the runoff slowing and infiltration increase. Please, report discharge in mm.

OK

Page 12, lines 14 and subsequent: "Modification" and "erosion surfaces" are not appropriate terms here, as discussed above. The "increase in erosion surfaces" is contradictory respect to the small changes in these units as described in Page 10 line 9. Here there is confusion between soil properties and landscape units, please be more explicit.

OK thank you for the suggestion.

Page 12, lines 20 and subsequent: " the result is an increase of xxx mm/year of the discharge for the past period..."

OK

Page 12, line 28: mind the confusion between soil and landscape unit

OK

Page 14, line 36: "... and soil properties may largely explain..."

OK

Page 15, lines 3-4: "The lack...concentrated runoff": There is a melange of causes and consequences, yet, the change from sheet to concentrated runoff must be demonstrated.

OK. Runoff concentration is best observed during field survey (new rills, sometimes cutting through sand / silt bars, and vegetation changes from tiger bush tickets perpendicular to the slope to scattered trees like Acacia ehrenbergiana growing along rills parallel the slope. Hiernaux et al. 2009, Dardel et al. 2014a)

Page 15, lines 13-14: See the note above on channel entrenchment.

OK

Page 15, line 14 and subsequent: "Our work has shown that enhanced and concentrated runoff results in an increase in both the number and the length of channels, therefore increasing the drainage density and diminishing the travel time for water to reach the drainage network" : This is not shown in the results above.

See comment above about this. We have rephrased and stick to drainage network development.

Page 15, line 19: "Our results suggest that..."

OK

Page 15, line 28: "are simulated as part of vegetation..."

OK

Page 15, line 33: "surface runoff is observed and simulated to decrease..."

OK

Page 15, lines 36-27: a preliminary test should be made changing the fine temporal structure of rainfall, as suggested above.

See comment above.

Conclusions: this section should be rewritten after the revision of the manuscript, but it is important to bear in mind that in this case the model approach may be useful to “investigate” or to “shed some light on” the paradoxical evolution in the Sahel, but not to “understand” it.

OK, we agree with this statement. This has been done. Thank you for the suggestion.

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 have changed 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 have made it clear in the revised manuscript.

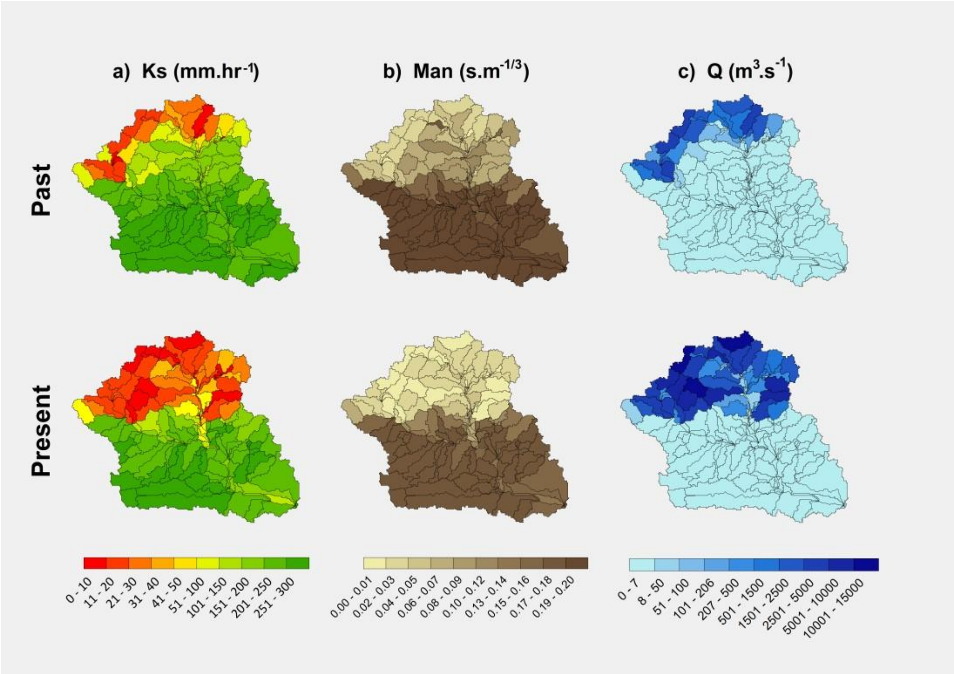
iii) The available data: The main problem is that only "annual" water outflow is available, reconstructed by the author for some years (see Table 1)! Moreover, one rain-gauge is available on the catchment, and data at a fine time step (5 min) are only available for given periods. The lack of analysis 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.

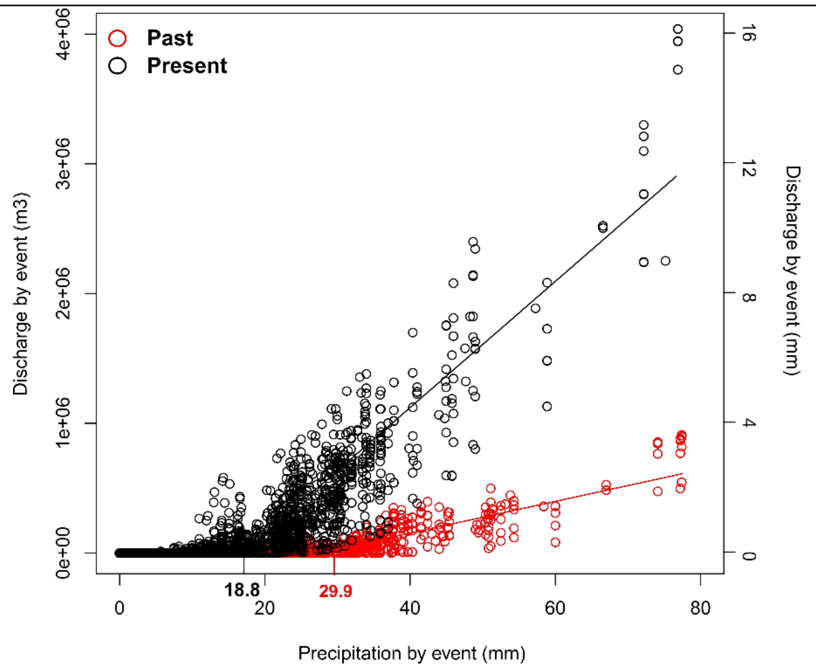
First of all, we propose to add additional figures (one with maps of Ks and MAN for Past and Present, and one figuring runoff versus rainfall for all events of the Past and Present, see below). Thank you for suggesting adding information on the spatial and temporal features of hydrology and changes over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

Then, we have explained 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 has not provided the real 5-min intensity for this event, but have on average provided 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)

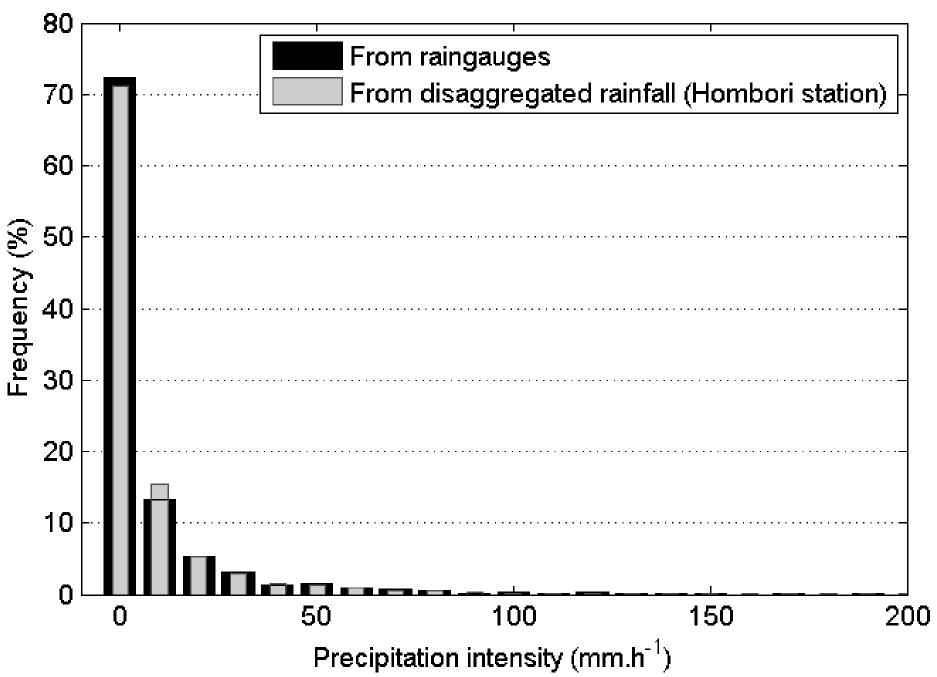
New figures: The figure below shows the impact of the changing landscape on the Manning roughness coefficient and the saturated hydraulic conductivity in the northern part of the watershed. These modifications have led to doubling the contributing area.



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.



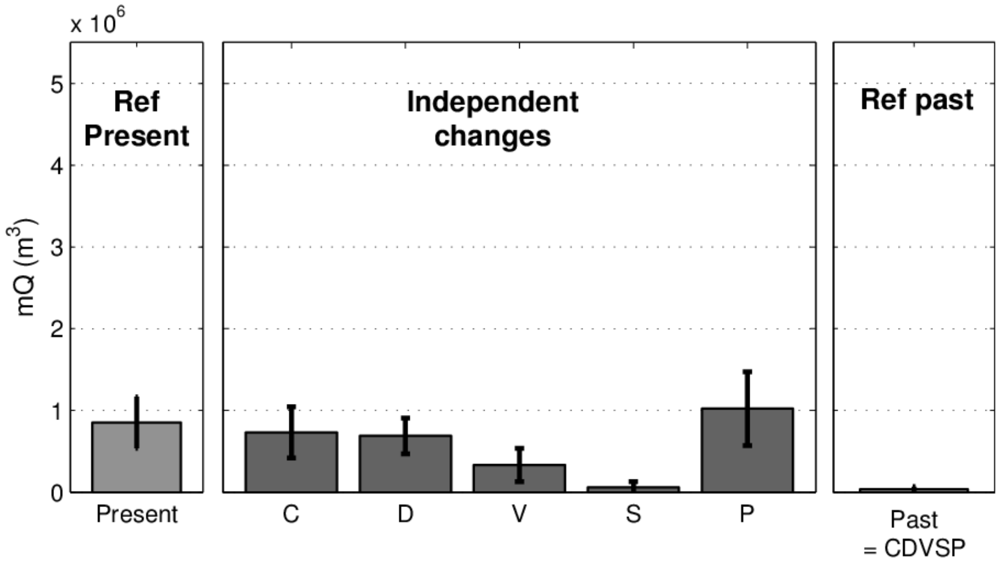
Last, the figure below shows a comparison between histogram of rainfall intensity of two different sources of rainfall (disaggregated and 5-min raingauges). There are quite comparable, particularly for the high intensities which are the most important for runoff production.



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.

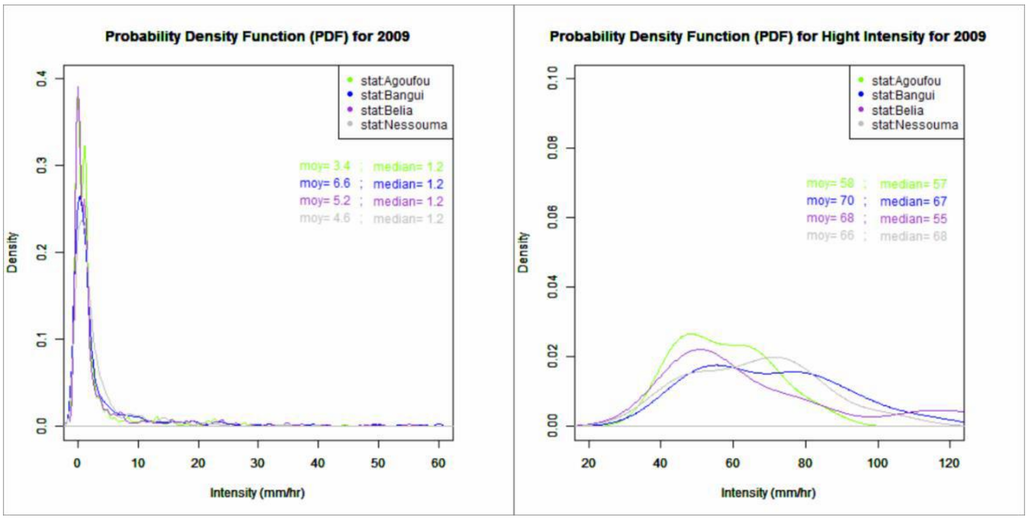
We agree we can provide more information on uncertainty, which is also an important point. For observational data, a full analysis of the uncertainties is detailed in Gal et al., 2016 Journal of Hydrology). We have given more details about this in the revised manuscript.

For the uncertainties on the planes parameters, we have also provided 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 have included 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 have been 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. OK, thank you

- 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".

OK

- The title of the paper must be in accordance with the objectives announced. OK, the title has been changes

- 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.

We prefer to separate study site and available data but thank you for the suggestion

- 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)?

We cannot estimate it. The sensitivity analysis made on planes properties, shows that even absolute values changed, the rank of factors does not changed. Furthermore, K2 defines one mean hydrological parameters set for each planes and so can smooth any uncertainty on the delimitation of units on maps.

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

We have provided more information on the drainage network definition.

- The Manning coefficient MAN has a unit ((mˆ1/3 / s)

$s.m^{-1/3}$ actually but yes thank you

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

OK

- 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).

RC#5

Referee comment on "Modeling the paradoxical evolution of runoff in pastoral Sahel. The case of the Agoufou watershed, Mali" by Laetitia Gal et al. (Hydrol. Earth Syst. Sci. Discuss., doi: 10.5194/hess-2016-623, 2016.)

This reviewer largely agrees with many of the comments already expressed by reviewers RC2 and RC4. Given the numerous issues expressed I feel the paper should be reframed and possibility retitled along the lines expressed by reviewer RC3 whose last suggestion was "Conclusions: this section should be rewritten after the revision of the manuscript, but it is important to bear in mind that in this case the model approach may be useful to "investigate" or to "shed some light on" the paradoxical evolution in the Sahel, but not to "understand" it." A new title might be something like "Exploration of the paradoxical evolution of runoff in the pastoral Sahel - Agoufou Watershed using available data and a watershed model."

We thank reviewer 5 for providing valuable comments and remarks on the first manuscript, as well as on the comments/suggestions of the other reviewers. We appreciate the suggestions based on a deep knowledge of the K2 model.

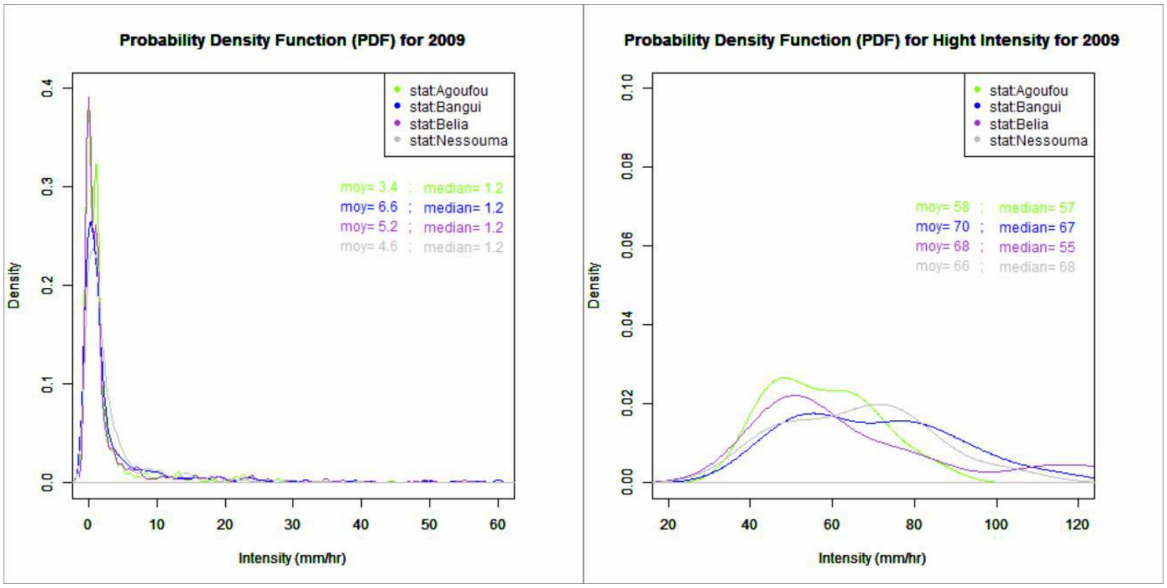
The title have been modified following your suggestions, thank you. Also, we have moderated the terms used in the conclusion and in the manuscript to emphasize we present modelling-based conclusions.

The author could then stress that the model selected could be one of many for this investigation, but K2 was selected for x, y, and z reasons as a tool to investigate possible reasons for the paradoxical evolution of runoff in the Agoufou watershed. Within the constructs of the model, its structure, and the assumptions inherent in the model it was felt it could be used to conduct a relative ranking of various factors and watershed attribute changes contributing to the paradox. Using other models one might come to different conclusions or attributions but the authors could encourage others to conduct comparable "detective" investigations to better understand factor contributing to the paradox.

A preliminary 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 objectives. In addition a model/data intercomparison project, called ALMIP2 for AMMA Land Surface Model Intercomparison phase 2, was 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 and upon request to M. Grippa). The results highlighted the difficulty of models to distinguish between shallow or silty soils generating the runoff ending up in ponds and no-runoff areas, like sandy deeper soils, which infiltrate all rainfall. LSMs have been found to be too sensitive to rain and not enough to soil properties. These various arguments explain why we have chosen the Kineros2 model.

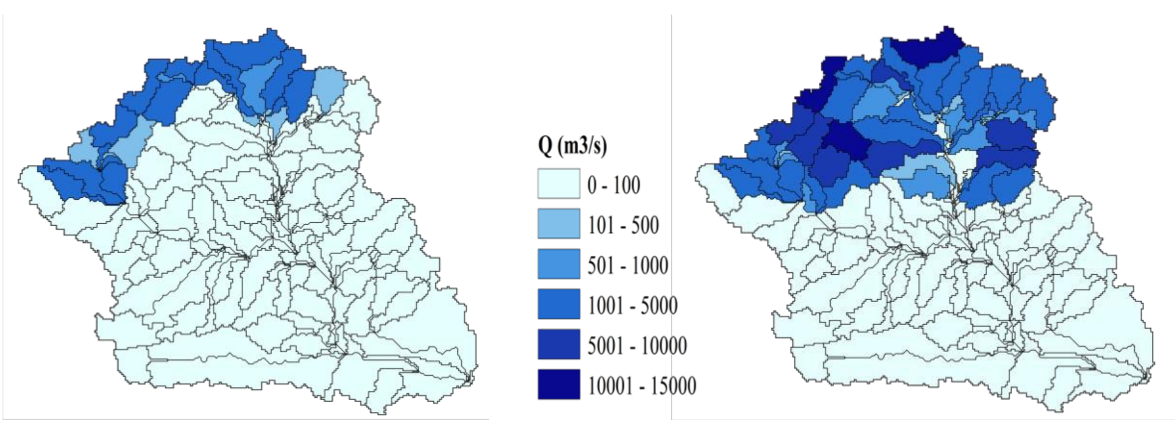
As pointed out by the other reviewers the uniform precipitation assumption for a basin this size constitutes a major simplification and calls into question the ability to carry out a defensible model calibration and validation. Al-Qurashi et al. (2008) applied K2 to a 734 km^2 arid watershed with 7 rain gauges where a "parameter set which gave best calibration performance over any combination of 26 events did not generally produce acceptable performance (defined as within 30% of observed) when used to predict the 27^{th} event". In this and similar situations, the authors noted that "data sets typically used for distributed (or semi-distributed) rainfall-runoff modeling in arid regions cannot provide an accuracy which justifies the effort and expense of this (K2) modeling approach. The limitations imposed by relatively sparse observations of rainfall are of particular concern" (Al-Qurashi et al., 2008, p. 104).

The uniform precipitation hypothesis is an important point and has required additional analyzes not detailed in the manuscript. The figure below shows an example of the rainfall PDF derived for different AMMA-CATCH stations for an average precipitation year (There are no others stations than those identified in Fig.1, so we have no station in the north of the Agoufou watershed). 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. In addition, the figure below (that has been added to the revised manuscript) shows that the contributing part is located to the north of the catchment. Therefore, only one third of the watershed is concerned.

Past (JAS) **Present (JAS)**



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). 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 reason that this would change the difference between the past and present case runoff, which is the main focus of the paper.

Qurashi et al. (2008) analyzed their results at the event scale unlike we do. We analyze the results on an annual scale and 15-year average scale. The point is indeed to analyze the results in a statistical way in the light of uncertainties related to the precipitation.

To remove this major limitation and use K2 as a tool to explore causes of the runoff increase this reviewer suggests taking a relative change approach as advanced by Goodrich et al. (2012) and Sidman et al. (2015) for post-fire watershed assessment in watersheds that often do not have any rainfall-runoff data available for calibration and validation. In this approach a pre-fire land cover map is used to parameterize the watershed and conduct a simulation with a spatially uniform design storm. The burn severity map is then used to alter model parameters based on prior research and analysis of the effects of burns on cover and soil hydraulic properties. A second post-fire simulation is then conducted using the same rain storm. The results can then be spatially differenced to analyze changes. For the author's study the present and past model parameterizations based on analysis of historic and current land cover and soils data are analogous to the pre- and post-fire conditions. The authors could pick one of their most trusted rainfall data sets (perhaps when they had high temporal resolution measurements) and use that rainfall input data set for both the past and present watershed model parameterizations. Given one of their conclusions (last paragraph) was that climatic and precipitation changes from past to present appeared too little or no impact on the findings this would further justify the approach noted above. By doing so the authors would isolate the analysis on watershed changes as they would be using identical input drivers. This would still be directly in line with the stated objectives of their study.

In fact, if we understand correctly, using 5-min data from a look-up-table (i.e. well documented storms) is similar to what you propose, but done in a more systematic way since all rain events are considered. This holds true for the Present compared to C, D, V and S simulations. Only the P (precipitation) simulation uses different 5-min evens, corresponding to Past daily rainfall.

Technical Comments:

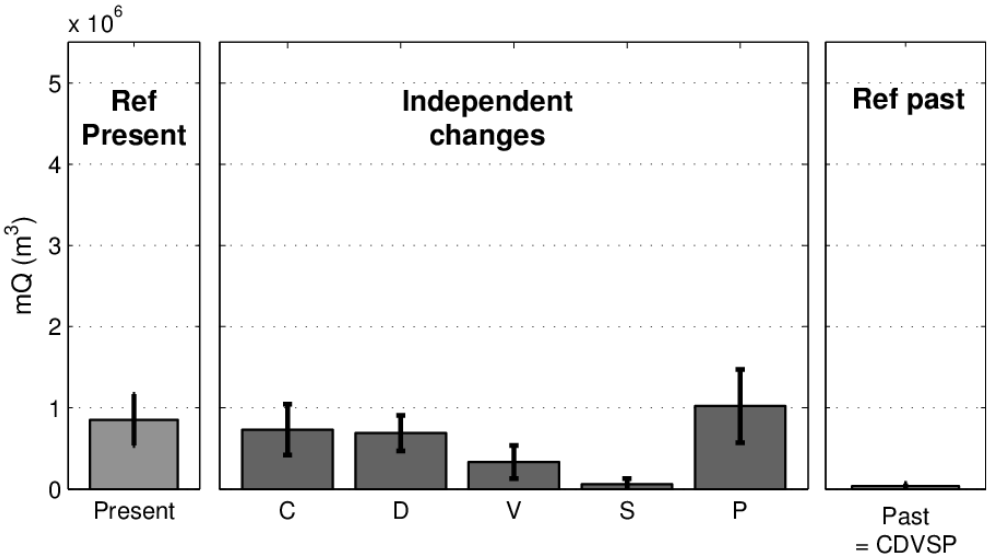
The authors have confused the meaning of the CSA or contributing source area. This is the drainage area required it initiate the head of a first order channel and effectively defines the level of geometric complexity of the watershed with a smaller CSA (percent of drainage area or absolute area) resulting in more watershed modeling elements. The channel source area modeling elements are those that drain to the head of a first order element. The remaining upland or hillslope modeling elements (planes – they can be curvilinear as well) contribute laterally to channel modeling elements.

That's right, CSA was used for all planes. This has been corrected.

Regarding the questions by other reviewers of K2 model sensitivity the author's should review and cite Yatheendradas et al. (2008) who conducted a thorough analysis of variance. In their analysis, model prediction uncertainties are dominated by precipitation input uncertainties (another reason in suggesting the approach noted above). For K2 model parameters a multiplier on the Ksat of overland flow model elements and the Manning's roughness multiplier on overland flow model elements were the most sensitive parameters while the channel roughness multiplier was also quite important. Given this information it is odd that the authors selected the Ksat of the channels and not of the overland flow planes for calibration. Note that Ksat of channels and Ksat of hillslope elements do interact. The relatively low calibrated Ksat channel value that the authors found could easily be the result of a higher Ksat on the hillslope elements resulting in lower lateral runoff inflow into the channels.

We agree with the high sensitivity or runoff to planes parameters. Indeed, it is one conclusion of our study (Soils and Vegetation changes on planes ranking first and second).

We have explained the rationales of our approach in a more precise way in the revised manuscript: Not to calibrate the planes parameters (which are constrained by our land surface maps). Calibrate channels only, which are less known, with the only objective to check than plane runoff produces a total flow consistent with observation, with plausible values of the channels parameters.



To make it clearer, we have performed a sensitivity test to planes parameters (see figure above), multiplying planes Ks by 2.5 and planes MAN by 1.75 (based on literature review by Casenave and Valentin, 1989). The absolute values of total runoff changes as expected, but the ranking of the factors is the same. This gives robustness to our findings.

(Technically, we did not use the multipliers because they modify the parameters of the planes AND the channels. Adding this feature, either adjust planes or channels, is in discussion for implementation in KINEROS2, Shea Burns, pers. com).

The calibration of channels parameter plays a minor role, ensuring only that the planes description results in simulated runoff which can match observations with plausible channel parameters. The resolution of the satellite and aerial photographs used to analyze the past and the present does not allow an identification of channel properties and their possible changes over time.

Given the author's finding of the importance in the change drainage density and channel characteristics two items are suggested:

1. Did the author's use the default values for channel cross-sectional geometry? If so these value were derived from regressions relating X-S measurements to easily derived variables from GIS operation on watershed data as obtained at the Walnut Gulch Experimental Watershed in SE Arizona, USA (Miller et al., 2000). The Walnut Gulch relationships are likely to be a poor representation of the channel cross sectional characteristics of the Agoufou watershed. It is suggested that the authors gather some field measurements from the Agoufou watershed. At least from several stream orders so they might be scaled across all the channels in the study watershed.

We only changed channels width (10 ans 11 m) to fit observations and checked that channel depth was correct (.4 to .7m).

2. Instead of altering the aspect ratio of the overland flow (plane) hillslope elements a watershed discretization can be derived from for each (past and present) channel network (contact Shea Burns for details).

It was probably not clear in the first manuscript, but changing the planes aspect ratio reproduces exactly the elongation of the channel network (since lateral plane's width corresponds to channel length). Changing CSA was considered also but there was a risk of changing plane properties in an uncontrolled way (changing CSA with DEM doesn't seem straightforward in K2). That would have complicated the interpretion changes between the past and present cases.

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The ~~Modeling the~~ paradoxical evolution of runoff in pastoral Sahel: Analysis ofthe hydrological changes over~~Sahel. The case of~~ the Agoufou watershed (~~,~~ Mali) using the KINEROS-2 model.

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Abstract

In the last decades, the Sahel has witnessed a paradoxical increase in surface water despite a general precipitation decline. This phenomenon, commonly referred to as "the Sahelian paradox", is not completely understood yet. The role of cropland expansion due to the increasing food demand by a growing population has been often put forward to explain this situation for the cultivated Sahel. However, this hypothesis does not hold in pastoral areas where the same phenomenon is observed. Several other processes, ~~have been suggested to account for this situation~~ such as the degradation of natural vegetation following the major droughts of the 70ies and the 80ies, the development of crusted top soils, the intensification of the rainfall regime and the development of the drainage network, have been suggested to account for this situation.~~network.~~

In this paper, a modeling approach is proposed to explore, quantify and rank the different processes that could be at play in pastoral Sahel. The KINEmatic EROSion model (KINEROS-2) is applied to the Agoufou watershed (245 km²), in the Gourma region in Mali, which underwent a significant increase of surface runoff during the last 60 years. Two periods are simulated, the "past" case (1960−1975)~~(1960-1975)~~ preceding the Sahelian drought and the "present" case (2000−2015).~~(2000-2015).~~ Surface hydrology and land cover characteristics for these two periods are derived by the analysis of aerial photographs, available in 1956, and high resolution remote sensing images in 2011.~~-~~The major changes identified are: 1) a partial crusting of isolated dunes, 2) an increase of drainage network density, 3) a marked decrease in vegetation with the non-recovery of tiger bush and vegetation growing on shallow sandy soils and 4) important changes in soil properties with shallow soil being eroded and replaced by ~~giving place to~~ impervious soils. The KINEROS-2 model was parameterized to simulate these~~These~~ changes ~~were implemented independently and~~ in combination or independently. The~~in the KINEROS-2 model. The simulations~~ results obtained by this model display~~show~~ a significant increase of annual discharge between the "past" and the "present" case (p value < 0.001), which is consistent with observations, despite a slight overestimation of the past discharge. Mean annual discharges are estimated at 0.51×10^6 m^3 (2.1 mm.yr^{-1}) and 3.29×10^6 m^3 (13.4 mm.yr^{-1}) for past and present respectively.

Changes in~~Modification of~~ soil properties and vegetation cover (grassland and tiger bush thickets) are found to be the main factors causing~~explaining~~ this increase of simulated runoff,~~,~~ with the drainage network development contributing to a lesser extent. These results shed a new light on~~synergistic processes explain~~ the Sahelian paradox phenomenon in the absence of land use change, and call for further tests in other areas and/or with other models. The synergetic processes highlighted here could play a role in other Sahelian watersheds where runoff increase has been also observed.

Keywords: Sahelian paradox, Annual discharge, KINEROS-2, Agoufou watershed~~Evolution~~

1 Introduction

During the second half of the 20th century, the Sahel underwent a severe rainfall deficit, considered as the largest multi-decadal drought of the last century (Hulme, 2001; Nicholson et al., 1998), with extreme droughts in 1972-73 and again in 1983-84, that strongly impacted ecosystems, water availability, fodder resources, and populations living in these areas (Nicholson, 2005).

Responses induced by this deficit result in contrasted effects depending on the ecoclimatic zone considered. If the Sudano-Guinean zone displayed an expected decrease of surface runoff following~~during~~ the drought, the opposite situation was observed in the Sahelian zone (Descroix et al., 2009; Séguis et al., 2002, 2011).~~-~~First reported for a small watersheds in Burkina Faso by Albergel (1987), this paradoxical situation was also diagnosed by Mahé and Olivry (1999) for several other watersheds in West African Sahel, then by Mahé et al. (2003) for the right bank tributaries of the Niger river and by Mahé et al. (2010) for~~t~~ the Nakambé watershed. This phenomenon was also observed~~-~~ as West as Mauritania (Mahé and Paturel, 2009) and as East as Nigeria (Mahé et al., 2011) and as north as in~~. In~~ the Gourma region (~~,~~ Gardelle et al. ~~(~~2010)~~. reported a significant increase in ponds surface despite declining precipitations.~~ This regional phenomenon is commonly referred to as "the Sahelian paradox" and its causes are still debated.

Whether this situation is man-made or mostly a response to climate variability is of great importance for planning and management of water resources and development. The leading role of increased cropped surface and land clearance has been put forward in several studies carried out in cultivated Sahel (Favreau et al., 2009; Leblanc et al., 2008; Mahé and Paturel, 2009). Population growth in the Sahel is rapid and associated with important Land Use Changes (LUC) since the 50s.

However, the LUC hypothesis does not hold for pastoral areas commonly found in central and northern Sahel. In northern Mali for instance, an important area extension and flood duration of ponds and lakes has been observed (Gardelle et al., 2010), which has a large impact on local population and economy since the installation of people and livestock often depends on the presence of surface water. A similar evolution is suspected for other ponds and lakes in pastoral areas in Niger and Mauritania also (Gal et al., 2016). Changes in Land Cover (LCC), particularly in vegetation and soil properties, have been put forward as a possible explanation. Gardelle et al. (2010) suggested that the non-recovery of some ecosystems after the major droughts could be responsible for the significant increase in the surface of ponds in northern Mali. Vegetation degradation favors surface runoff via the acceleration of the overland flow and the reduction in the hydraulic conductivity properties. In addition, a reduction in vegetation cover can contribute to decreasing rainfall interception and soil protection against raindrop energy, favoring the ~~and~~ top soil crusting which again limits infiltration and trigger rainfall excess overland flow. The role of top soil crusting has been ~~have been~~ pointed out in several studies. ~~as possible explanation.~~

Sighomnou et al. (2013) suggested that vegetation degradation and land clearance in southwestern Niger have changed soil surface properties and infiltration capacity enough to increase Hortonian runoff. A general decline in vegetation cover generating increased soil erosion and crusting and in turn an increase of surface runoff has been put forward by Leblanc et al. (2007), Hiernaux et al. (2009a), Toure et al. (2010) or Aich et al. (2015).

~~The LCC hypothesis was also supported by Gardelle et al. (2010) for pastoral Sahel, who suggested that the non-recovery of some ecosystems after the major droughts could be responsible for the significant increase in the surface of ponds in northern Mali.~~ Another possible factor cited in the literature is the development of the drainage network. Leblanc et al. (2008) analyzed time series of aerial photographs in southwestern Niger and reported a spectacular increase in drainage density, as it was also found by Massuel (2005).

It should be noted that interactions and feedbacks among these different drivers are quite common in dry lands. For instance, the development of impervious surfaces may favor rapid runoff, possibly gully erosion, which in turn may deprive vegetation from water,~~soil moisture,~~ resulting in vegetation decay and more imperviousness. Last, a change in daily rainfall regime could be a possible cause of increased runoff. A slight increase in large daily rainfall has been suggested by Frappart et al. (2009) and demonstrated by Panthou et al. (2012, 2014). This signal is mostly observed since the 2000, and does not imply a change in rainfall intensity measured at shorter time scale.

Although hydrological modeling is a valuable tool to investigate the mechanisms responsible for the Sahelian paradox, few modeling studies have been carried out so far, mainly addressing the impact of land use change and land-clearing on surface runoff (Aich et al., 2015; D'Orgeval and Polcher, 2008; Favreau et al., 2009; Li et al., 2007; Mahé and Paturel, 2009; Mahé et al., 2005; Séguis et al., 2004). This is partly due to difficulties of modeling hydrological processes in semi-arid regions, for instance in endorheic areas, but also to the limited historical data available to calibrate and validate hydrological models (see for example Li et al., 2007; Mahé et al., 2005). Furthermore, Grippa et al., (2016) analyzed the hydrological behavior of 20 different land surface models (LSMs) over the Agoufou watershed and showed their inability to correctly differentiate among shallow or silty soils, generating runoff, and deep sandy soils with high infiltration capability that dominate non-runoff areas. Attribution studies inferring the impact of the different factors detailed above on surface runoff are therefore lacking.~~Attribution studies inferring the impact of the different factors detailed above on surface runoff are therefore lacking.~~

The objectives of this study are:~~is:~~ 1) to analyze the soil, land cover and hydrological changes that occurred over the Agoufou watershed since the 50ies-and 2) to investigate how~~quantify and rank the impact of~~ these changes impact ~~on~~ surface runoff. In that purpose, the KINEmatic EROSion model (KINEROS-2) is used to simulate runoff over the past (1960-1975) and the present (2000-2015) periods.

2 Materials

2.1 Study site

The Agoufou watershed (**Fig. 1**) is located in the Gourma, a region of northern Mali delimited by the Niger Rive r-to the North and the border with Burkina-Faso to the South. This region has been extensively monitored by the AMMA-CATCH observatory (Analyse Multidisciplinaire de la Mousson Africaine - Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique) and before by ILCA (International Livestock Centre for Africa) and IER (Institut d'Economie Rurale in Mali) providing historical data (Hiernaux et al., 2009b; Lebel et al., 2009; Mougin et al., 2009).

As elsewhere in the Sahel, the climate is tropical semi-arid with a unimodal precipitation regime. The rainy season extends from late June to September, and is followed by a long dry season. Precipitation comes from tropical convective events, 25 to 50 per year, brought by the West-African monsoon (Frappart et al., 2009; Vischel and Lebel, 2007). Its long term evolution has been characterized by a wet period between 1950 and 1970 followed by a long dry period with extreme droughts in 1972-73 and again in 1983-84. The last 15 years have shown a partial recovery of rainfall, with large events seemingly occurring more often (Frappart et al., 2009; Panthou et al., 2012). Average rainfall was 345 mm/yr over the 2000−2015 period and 382 mm.yr^{-1} over the 1960−1975 period. Evaporation was much higher than precipitation with averages of 3235 mm.yr^{-1} and 2930 mm.yr^{-1} for the two periods respectively.

The Agoufou watershed extends over 245 km² and ranges between latitude of 15.3 °N and 15.4 °N and longitude of 1.4 °W and 1.6 °W. The Gourma region is endorheic, which means that it is a mosaic of closed drainage watersheds that does not provide outflow to the Niger river and thus to the Atlantic Ocean. The Agoufou lake is the outlet of the watershed. As the majority of lakes and ponds in the region, it showed an important surface area increase~~-~~ over the last 50-60 years (Gal et al., 2016) and nowadays, typically reaches about 3 km² at the end of the rainy season.

Geology is characterized by~~The topographic watershed of the Agoufou lake lies on~~ Upper Precambrian schists and sandstones~~ leveled by a long history of erosion,~~ partially covered by staggered ferricrete surfaces (Grimaud et al., 2014), silt depositions and sand dunes. The study site has been extensively described in Gal et al. (2016). The northern part of the watershed (**Fig. 1**) consists of outcrops and shallow soils lying on sandstone, schist or iron pans. Some of these soils are fine textured soils (silt flats), which frequently generate runoff. The southern part is dominated by deep sandy soils with high infiltration capacity. The altitude range is 92 m, the average slope of the main reach is equal to 0.22 %.~~The upstream portion of the Agoufou watershed (Fig. 1) consists of shallow soils on bedrock (sandstone, schist or iron pans), mostly fine textured soils prone to crusting, interspersed with rock outcrops and iron pans that generate most of the runoff ultimately ending up into the lake. The downstream portion is dominated by deep sandy soils into which most rainfall infiltrates rapidly. The altitude range across the Agoufou watershed is of 92 m. The average slope along the 24 km long main reach is equal to 0.22 %, with 0.20 % in the 7 km upstream, 0.41 % in the 7 km midstream and only 0.08 % in the 10 km downstream section, where the reach flows through the sand dunes.~~

The vegetation is typical Sahelian vegetation with an herbaceous layer almost exclusively composed of annual plants, among which grasses dominate, plus scattered bushes, shrubs and low trees (Boudet, 1972; Hiernaux et al., 2009a, 2009b). Almost continuous on sandy soils, except for a few deflation patches and bare dune crests, the herbaceous layer is highly discontinuous on shallow soils and clay plains, leaving large bare areas prone to runoff. The density and crown cover of woody plants are low in average, usually between 0 and 5 % (Hiernaux et al., 2009b). Woody plants concentrate along drainage lines, around ponds, in the inter-dune depressions and also sometimes on shallow soils, with a regular pattern of narrow linear thickets set perpendicular to the slope known as “tiger bush” (Hiernaux and Gérard, 1999; Leprun, 1992). These thickets live on the water and nutrients harvested on the impluvium made by the bare soil upstream, and their development efficiently limit runoff further downstream (D’Herbès and Valentin, 1997).

Casenave and Valentin (1989), among others, have demonstrated that the Sahelian hydrological processes are largely dependent on land surface conditions: soil properties, crusting, topography and vegetation cover

(Albergel, 1987; Collinet, 1988; Dunne et al., 1991; Hernandez et al., 2000). Low soil infiltrability associated with the convective nature of the precipitation favors runoff generation by infiltration excess (Descroix et al., 2009, 2012; Leblanc et al., 2008; Peugeot et al., 2003) commonly known as Hortonian runoff.

The choice of this watershed has been motivated by tree characteristics: 1) This site is instrumented by the SO-AMMA-CATCH, which provides fields measurements on vegetation and soil characteristics, meteorological variables, and lake's height estimates over a long period of time (starting in 1984 for the long term ecological survey), as well as good field knowledge by co-authors. 2) the Agoufou lake has experienced a spectacular increase in inflow over the past 60 years despite the decrease in precipitation (Gal et al. 2016), which is a very good example of the Sahelian paradox and of the evolution of surface water observed more generally in the Gourma region (see Gardelle et al., 2010) and elsewhere in the Sahel (Mauritania and Nigeer, Gal et al., 2016). 3) This site is a pastoral watershed where agricultural activity is almost non-existent. It is thus different from the watersheds that were addressed by hydrological studies on the Sahelian paradox up to now. It can therefore shed a new light on the debate over land use versus land cover as possible explanation of the Sahelian paradox.

2.2 KINEROS2

Gal (2016) carried out a literature review of 20 different hydrological models (global, distributed and semi-distributed) in order to identify the most appropriate models to simulate hydrological processes in the study area and to meet the objectives of this study.~~KINEROS-2 description~~

The KINematic EROSion model (KINEROS-2) was considered the most suited among those analyzed.~~takes into account the hydrological processes dominating semi-arid hydrology.~~ KINEROS-2 (K2; Goodrich et al., 2011; Semmens et al., 2008; Smith et al., 1995) is the second version of KINEROS (Woolhiser et al., 1990). It is an event-oriented physically based model describing the processes of infiltration, surface runoff, interception and erosion for small watersheds and most of its applications concern arid and semi-arid areas~~watersheds~~ (Hernandez et al., 2005; Kepner et al., 2008; Lajili-Ghezal, 2004; Mansouri et al., 2001; Miller et al., 2002). The surface runoff simulation is based on the numerical solution of the kinematic wave equations (Wooding, 1966), solved with a finite difference method. It assumes that runoff can be generated by exceeding the infiltration capacity (Hortonian mechanism) or by soil saturation depending on rainfall intensity and soil properties (infiltration capacity). The infiltration process is based on the Smith and Parlange equation (1978) defined by soil and land cover parameters: soil water capacity (the difference between soil saturation capacity and initial saturation), saturated hydraulic conductivity, soil porosity, net capillary drive, pore distribution, roughness coefficient and percent of canopy cover. Evapotranspiration and groundwater flow are neglected (Mansouri et al., 2001) but K2 takes into account canopy interception and storage. Soil water is redistributed during storm intervals (Corradini et al., 2000) based on the Brooks and Corey relationship, corresponding to an unsaturated permanent flow.

The watershed is treated as a cascading network of planes and channel elements. Channels receive flow from adjacent planes and/or upslope channel. Each element is assigned homogeneous parameter values that describe geometry and hydrological parameters (slope, vegetation cover, soil properties, initial conditions etc.) and control runoff generation (Goodrich et al., 2011).

Element definition is done with the Automated Geospatial Watershed Assessment tool (AGWA) which is the GIS-based interface (Miller et al., 2007). From the topography, AGWA discretizes the watershed into sub-watersheds (or planes) according to~~ (depending on~~ the Contributing Source Area (CSA) defined by the user. The CSA is the minimum area that is required for initiation of channel flow. The number of sub-watershed (or planes) and the density of the channel network increase with decreasing CSA. Each plane is~~user), which are~~ considered as homogenous and its hydrological~~. Hydrological~~ parameters~~ for each pane~~ are derived from soil surface characteristics maps based on soil texture (FAO classes) and vegetation properties.

2.3 Input data

K2 needs four input datasets:~~ to run:~~ the digital elevation model (DEM), the soil map and the land cover map that are necessary to describe the watershed in term of hydrological and geometrics parameters and the precipitation data that are needed at a small time step (5 minutes) to take into account the short and intense rainfall events, typical of the Sahelian monsoon. The input data used in this study are summarized in Table 1 and described below. Further details and analysis of in-situ data can be found in Frappart et al. (2009) Guichard et al. (2009), Timouk et al. (2009) and Gal et al. (2016).

~~ and described below.~~

2.3.1 Digital elevation model (DEM)

Two DEMs,~~DEM,~~ with a horizontal spatial resolution of 30 meters, are commonly used in hydrological studies: the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM and the Shuttle Radar Topography Mission (SRTM) DEM. Studying two Ghana watersheds, Forkuor and Maathuis (2012) found that SRTM had a higher vertical accuracy than ASTER even if both DEMs provided similar geomorphologic structures. Moreover, ASTER was found to suffer from artifacts, mainly peaks, particularly in flat terrain, which proved difficult to remove through filtering (Isioye and Yang, 2013). For these reasons SRTM was retained for this study, although the DEM derived by ASTER was not markedly different in our case.

2.3.2 Soil and land cover images~~data~~

For the present period, a high-resolution GeoEye-1~~-~~satellite image (0.42 m) acquired on February, 17, 2011 is available through Google Earth. It is supplemented by a SPOT satellite image (resolution of 5 m) to cover the whole watershed (5 % of the watershed is not covered by GeoEye). For the past period, a series of aerial photography is~~photographs are~~ available from IGN Mali (ND30 XXIII 1956). Seven stereo pairs of images acquired in 1956 cover the whole watershed.

2.3.3 Precipitation and meteorological data

Two sets of precipitation data are used for the Agoufou watershed:

- Daily precipitation (DP) from the Hombori SYNOP meteorological station available from 1930 to 2012 through the Direction Nationale de la Météorologie du Mali, and completed until 2015 by the AMMA-CATCH observatory. This station is 15 km away from the Agoufou lake.

- Rainfall at a temporal resolution of 5minutes~~5 minutes~~ (5M) obtained from an automatic raingauge network operated over 2006-2010 by the AMMA-CATCH Observatory in the Gourma region (Frappart et al., 2009; Mougin et al., 2009).

Raingauges used in this study (Table 1 and Table 1and **Fig. 1**) were selected for their proximity to the study site and for the quality of the measurements series (few gaps).

In addition, relative humidity, air temperature, incoming short-wave radiation and wind speed derived from the Agoufou automatic meteorological station at a time scale of 15 minutes, are used as input to the grass layer sub-model (see Sect. 3.2.4 3.2.3).

2.3.4 Hydrological data

An indirect method developed by Gal et al. (2016) estimates the water inflow to the Agoufou lake which corresponds to the watershed outflow. This method uses a water balance equation that takes into account precipitation over the lake, infiltration, open water evaporation and changes in lake water storage. This last term is obtained by combining open water surface area, derived by high resolution remote sensing data (Landsat, SPOT and Sentinel2) or in-situ height measurements, and a relationship between area and volume. Annual and intra-annual watershed outflows are available for 17 years between 1965 and 2015, depending on the availability of the satellite data. A sensitivity analysis has been carried out to evaluate this methodology (described in details in Gal et al., 2016): it was found that errors on volume estimation and evaporation estimation are the most important and can both lead to under/overestimation of water outflow of about 10%.

3 Methods

3.1 Landscape units

Land cover and soils maps have been derived from satellite data for the present period (2011) and from aerial photographs for the past period (1956). For each period, four major groups of landscape units have been distinguished: sandy soils units (S), outcrops units (O), pedimenterosion surface units or "glacis" (P)(E) and flooded zones units (F) which are further divided into subunits with different soil and land cover types, and hydrological properties (Table 2). This classification is based on long term ecosystem survey(Mougin et al., 2009)Table 2). This classification is based on long term ecosystem survey (Mougin et al., 2009) and studies carried out in the Sahel by Casenave and Valentin (1989), Valentin et Janeau (1988), Kergoat et al. (2015)(in prep) and Diallo and Gjessing (1999).

For the past period, photo interpretation of stereo-pairs is used so that the relative elevation of the different units can be derived from the three dimensional view, which is helpful for identifying units on panchromatic images. For the present period, the very high resolution of satellite images and the true color composites allows discriminating each unit rather easily. For both periods, units have been delimited independently and manually to maximize consistency. When photo-interpretation is not sufficient to discriminate some landscape units, a conservative option is applied, that consists in keeping the changes between present and past are considered null.minimal.

3.2 Model setup and watershed representation

The objective of this work is to use the K2 model to analyze changes between the past and present periods and to employ the model as a diagnostic tool. For this reason, model parameters are prescribed as realistically as possible for these two periods and calibration is kept at minimum in order not to mask out or distort the impact of observed landscape evolution on past and present surface runoff. The only calibrated parameters are those for channels since these are the least known from literature and they are difficult to identify with precision from remote sensing. Therefore, the change attribution study is carried out for planes only, which are not calibrated. Details on the model setup and on the determination of the different parameters are given in the next subsections.

3.2.1 Rainfall temporal disaggregation

Simulation of the Hortonian runoff associated with Sahelian convective rainfall requires precipitation data at a small time scale, typically of the order of a few minutes or tens of minutes. For the majority of the Sahel meteorological stations, historical rainfall data are available on a daily time step only, which makes temporal disaggregation necessary.

The temporal downscaling precipitation method applied in this study consists in replacing each daily precipitation (DP) event by an existing 5-minutes (5M) series having the same daily amount. To that end, a Look-Up-Table (LUT) of all 5M events from all automatic raingauges was built. It comprises 612 events spanning 0-144 mm per day.

To document the dispersion caused by temporal disaggregation, for For each DP event, ten 5M events of the LUT are retained to compose tenperform ensemble members.K2 simulations, in order to span the variability of 5-minutes intensity that may correspond to a given daily amount. These ten 5M events are randomly chosen among all events within 3 mm of the DP event total. If less than ten 5M events exist in the LUT, the interval is widened to -5/+5 mm or to -10/+10 mm and if necessary, the closest value is retained. Most of the time, intervals are less than 3 mm wide (76% of events). The 5-minutes rates are rescaled so that the daily total amounts are the exactly same.

The temporal disaggregation of daily data creates variability in the 5M precipitation forcing caused by the difference between the 5M events from the LUT and the rainfall actually seen by the watershed. Therefore, analyses are carried out on the ensemble mean (annual means and 15-year average), which smoothes out this noise.

Before the temporal disaggregation, the rainfall time series are split into events delimited by at least two days without rain. Events are considered independent, implying that the soil recovers its initial moisture conditions at the beginning of each event. The time required to delimitate independent events has been determined using soil moisture data available via the AMMA-CATCH observatory (see De Rosnay et al., 2009).

Before the temporal disaggregation, the rainfall time series are split into events delimited by at least two days without rain. Events are considered independent implying that the soil recovers its initial moisture conditions at the beginning of each event.

We further assumed that the rainfall cells are large enough to be considered uniform over the entire watershed. The analysis of the 5-minute rainfall events densities for the whole stations available, Gal (2016), shows that the probability density functions are similar among the different stations close to the water basin (see **Fig. 1**), especially for the high intensities that are the major contributors to runoff. In addition, the cloud top temperature, derived by MSG remote sensing data, was also analyzed, confirming that the rainfall cells in this region are generally larger than the watershed area (see Gal, 2016 for more details). However, at the event scale, spatial variability in Sahelian rain fields At the event scale, spatial variability in Sahelian rain fields (Le Barbé et al.,

2002) can be important even at the 10 km scale typical of our basin. This variability is significantly smoothed out at the annual time step but still persists and constitutes an uncertainty.. Therefore, K2 simulations will be best evaluated in a statistic way (ten members considered). The accuracy is expected to increase when periods of several years are averaged.

3.2.2 Watershed complexity

As mentioned in Section 2.2, theThe CSA controlsdetermines the level of geometric complexity in the discretization of the watershed and the density of the channel network (Thieken et al., 1999). with higher CSA producing more elements and a more developed drainage network. Ideally, the complexity of the simulated watershed is consistent with the watershed soil heterogeneity as well as with the spatial resolution of the simulated processes (Canfield and Goodrich, 2006; Kalin et al., 2003; Lane et al., 1975). According to Helmlinger et al. (1993), the optimal CSA depends on the case study, but a value smaller than 2.5 % of the total watershed area, is commonly selected. For this study, a the CSA corresponding to 1 % of the total watershed was selected, so that de telle sorte que the drainage network development corresponds to the drainage network common to found in both 1956 and 2011, and to reach a good compromise between simulation time, watershed complexity and homogeneity of the planes is reached (**Fig. 2**). The flow direction and the flow accumulation are then derived from the SRTM DEM, leading to): 174 planes with a mean area of 1.4 km²and a "DEM-derived network". have been retained, which corresponds to a CSA of 1 % of the total watershed area.

The same CSA have been retained for the present and the past cases, assuming that the broad features of the DEM did not change between the two periods (topography and the (slopes of cascading planes). However, the drainage network has changed between these periods. To account for this, the DEM- -derived network, which corresponds to the common network between 1956 and 2011, has been modified in some sub-watersheds to match the network development observed by remote sensing in 2011. To that end, the aspect ratio of the planes in these sub-watersheds is adjusted to increase the channel length and keep the plane area constant, by multiplying plane width and dividing plane length by the same number. This number corresponds to the ratio of observed network length toversus DEM-derived network length for each sub-watershed. The alternative method of changing CSA to change the network between the past and the present cases was not retained, since it would also change planes size, location and properties in an uncontrolled way, which could complicate the interpretation of the results.

3.2.3 Derivation of soil characteristics

FAO codes used by AGWA are assigned to all landscape units defined in Table 2Table 2 to match as closely as possible the soil texture and depth, known from field survey and previous knowledge of the study region. Table 3Table 3 summarizes the hydrological parameters assigned to each landscape unit by AGWA (based on laboratory analysis from soils texture of the world and pedotransfert function) and, used in K2 simulations. The initial saturation, -expressed as a fraction of the pore space, filled, is estimated for each plane to be 20 % of the maximum soil saturation but no less than 0.001 (the minimum required by K2).

3.2.4 Derivation of vegetation characteristics

Landscape units bear six different forms of vegetation: grassland and trees (GT), grassland (G), sparse trees (T), tiger bush tickets (TB), woody plant (W) and no vegetation (R), with different combination of herbaceous and woody plants (Table 4). Herbaceous plants are dominated by annual grasses and forbs, which grow rapidly during the rainy season and dry and decay rapidly after the last rains. The Manning's roughness coefficient (Man) is particularly sensitive to vegetation cover (Table 4). The saturated hydraulic conductivity (Ks) is also increased when plants are present following K2 equations. Interception is considered negligible because of the nature of the precipitation (high intensity and high winds during convective storms) and because of the usually low values of Leaf Area Index (LAI) found at the study site (Carlyle-Moses, 2004; (Mougin et al., 2014).

The seasonal dynamics of the grass canopy cover (CC) has been simulated with the STEP vegetation model (Mougin et al., 1995; Pierre et al., 2016)1995). It is driven by historical daily precipitation recorded at the Hombori station and daily meteorological data (short-wave incoming radiation, air temperature, relative humidity and wind speed) recorded every 15 minutes.. For the latter, a mean annual climatology is obtained using data from the Agoufou automatic weather station operating from 2002 and 2010. STEP being also dependent on soil texture and depth, it is run for deep soils and shallow soils (sand sheet 3 cm deep) separately to provide canopy cover over these different soils (CCd and CCs respectively). The relation between the Manning's roughness coefficient (MAN) and the percent of canopy cover (CC) is derived from several LUT, including NALC (North American Landscape Characterization) and MRLC (Multi-Resolution Land Characterization) provided in AGWA, and reads as follows (Eq. (1)):

$$MAN = 0.008 * CC \qquad (1)$$

For land cover types other than grasslands, constant values for ManMAN and CC arewere attributed based on ecosystem survey, GeoEye-1 imagery and K2 literature.

The saturated hydraulic conductivity (Ks)(KS) value based on the soil texture is modified (Ksnew;adjusted (KSnew; mm/hr) to take into account the effects of plants (Stone et al., 1992) as follows (Eq. (2)):

$$KSnew = KS \times e^{(0.0105 \times CC)} \qquad (2)$$

3.3 Derivation ofModel Calibration and Validation

3.2.5 Model calibration is performed by tuning channel parameters

Channel properties (MAN and KS) since channels parameters are less documented than the plane parameters. Considering the material in the channels (mostly a fine texture sandy loam, no gravels, few bedrock outcrops), the rather simple geometry (few braided channels) and the low number of scattered trees (found in the downstream part), a Man between 0.025 s.m$^{-1/3}$ and 0.032s.m$^{-1/3}$ would be the best guess (Barnes, 1987). The best guessCalibration is carried out for Ks, assuming the material is a mixture of silty soils and sandy soils, which are eroded in the upper watershed, gives a somewhat larger interval, ranging from 25 mm.hr^{-1} (silt dominated, using Cosby pedotransfer function or the AGWA scheme) to 50 mm.hr^{-1} (sandy dominated soils). Instead of taking the mean values of these intervals, which would give Man = 0.0285 s.m$^{-1/3}$ and Ks = 37.5 mm.hr^{-1}, we preferred to use an optimization method using the annual discharge over the 2011−2015 ~~the~~ period ~~2011-2015~~ (n=5). This period ~~which~~ benefits from numerous and accurate observations (named thereafter channel setup period). The benefit of the optimization is to check that the runoff simulated over the planes matches the observed flow at the outlet with reasonable values of the channel parameters. ~~.~~

A total of thirty sets of Ks~~KS~~ and Man~~MAN~~ parameters values were~~are~~ used to sample the 10−50 ~~10-50~~ mm.hr^{-1} and 0.01−0.05 s.m$^{-1/3}$ ~~0.01-0.05~~ domain, corresponding to large intervals derived from general literature ~~values~~ for semi-arid zones (Chow, 1959; Estèves, 1995; Peugeot et al., 2007). Assessment of the channels parameters is not fully automated and requires a large number of simulations and post processing, hence the limited number of parameter values tested. Each set of parameters is used to run the ten simulations corresponding to a disaggregated precipitation ensemble (see Sect.3.2.1 ~~3.2.1~~). Parameters leading to the lowest~~minimum~~ bias (Eq. (3)) as well as a reasonably low Root Mean Square Error (RMSE) value (Eq. (4)) on the annual discharge are retained and~~. These optimum parameters are then~~ used ~~to run K2~~ for all simulations (past and present periods).~~the validation period, which consists of years with available discharge observations during the 2000-2010 period (2000, 2001, 2002, 2007, 2009 and 2010; n=6).~~

$$Bias = \left(\frac{\sum sim - obs}{\sum obs} \right) \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (obs_i - sim_i)^2} \quad (4)$$

Where *sim* is the simulated annual discharge, ~~and~~ *obs* is the observed annual discharge at the time *i* and *n* is the number of data available. ~~.~~

3.2.6 Model evaluation

K2 is evaluated in terms of bias and RMSE for all years with available discharge observations during the 2000−2010 period (2000, 2001, 2002, 2007, 2009 and 2010; n=6, named validation period) as well as for all years with available discharge observations over the past period (1965, 1966, 1973, 1975, n=4). The years of the channel setup period (2011−2015) are not considered in the evaluation.

~~3.4~~3.3 Reference and attribution simulations of the Agoufou watershed

Two reference~~s~~ simulation cases are designed together with a suite of academic simulations to quantify and rank the effects of the landscape and meteorological~~major~~ changes observed over time.

The first reference simulation is the “present case”, which builds on the soil and vegetation map of 2011, with a simulation period extending from 2000 to 2015 (n=15). The present case, which has the highest number of observations available, combining the channel setup and evaluation period,~~Given that this period has been subjected to calibration and validation, the present case~~ is considered as the “baseline” simulation. The second reference case is the “past case”, which builds on the soil and vegetation map of 1956, with a simulation period extending from 1960 to 1975 (n=15).

From the present case, a suite of landscape~~environmental~~ changes, identified through~~by~~ the comparison of the Agoufou watershed in~~between~~ 1956 and 2011 (see Sect.4.1), lead to simulations C, D, V and S, and a meteorological change leads to simulation P. These changes~~ 4.1),~~ are implemented in the model~~ (simulations C, D, V, S and P),~~ first independently, then in combination. The simulation setup is summarized in Table 5 together with the associated forcing.

The impact ~~(*Ex* in %)~~ of the different factors~~,~~ considered in the different simulations is expressed as a fraction of the difference between present and past mean annual discharge (*Ex* in %, Eq. (5)), with~~(3)), where~~ 100 % corresponding~~corresponds~~ to the past discharge and 0 % to the present.

$$Ex = \frac{(AQpr - AQx)*100}{(AQpr - AQpa)} \qquad (5)$$

Where~~where~~ *AQpa* is the past annual discharge, averaged over 1960−1975,~~1960-1975,~~ *AQpr* is the present annual discharge averaged over 2000−2015~~–2015~~ and *AQx* the annual discharge of each simulation. The different factors can therefore be ranked according to their effect on runoff. Additional simulations (CD, VS, and CDVS) also address the effects of factors combination.

3.4 Sensitivity analysis and spatial evolution

A sensitivity analysis was carried out to assess the robustness of the model in ranking the factors responsible for the increase of surface runoff, considering the uncertainties associated to planes and channels parameters.

According to sensitivity studies previously carried out for K2 in semi-arid area, the Ks and the Man are the most important parameters affecting the simulated surface runoff (e.g. Al-Qurashi et al., 2008; Smith et al., 1999). A first sensitivity test was carried out on planes Ks and Man. The range of variability in plane parameters was based on data compiled by Casenave and Valentin (1989) for Sahelian soils, resulting in a factor of 2.5 for Ks and 1.75 for Man intervals. A second sensitivity analysis was carried out for the channels parameters, to compare the parameters giving the lowest RMSE and the lower bias during the channel setup period (2011-2015).

To represent the spatial evolution of these two sensitive hydrological parameters (Ks and Man) and surface runoff (Q) within the watershed, watershed maps were constructed for the monsoon period over the past and the present period.

4 Results

4.1 Soil and land cover maps derived for 1956 and 2011

The 1956 and 2011 land cover maps are presented in **Fig. 3a** and **Fig. 3b**, together with the corresponding drainage networks. For each landscape unit, the difference between these two periods has been computed (**Fig. 3c**).

Drainage network and flooded zones (F): The drainage network significantly increased between the two periods, with a total channel length of 71 km in 1956 against 104 km in 2011, corresponding to a drainage density increased by a factor of~~–~~1.5. Four zones (Z1, Z2, Z3, and Z4) underwent a particularly strong development of the drainage network (Table 6 and **Fig. 4**~~and Fig. 3~~). Furthermore, a fraction of the watershed, located in the western region, has become a contributing area of the watershed in 2011, as can be seen by the active drainage network development. Floodplains (F1) have also expanded from 6.5 km^2 in 1956 to 12 km^2 in 2011. This change coincides with an important increase of the open water area (F2), especially marked for the watershed outlet (the Agoufou lake).

Sandy soils (S): Sandy dunes (S2) and deep sandy soils (S3) exhibit limited changes. The total surface of these two units is 54 % of the total watershed in 2011 against 60 % in 1956. The conversion of S2 into agriculture enclosure (S4) explains most of this change, since enclosure occupy 10 km^2 in 2011 against 2.5 km^2 in 1956. Isolated dunes (S1) are found at the same location for both periods, but have been eroded and partially encrusted. Today, approximately 30 % of their surface is covered by crusts (i.e. 30 % of S1 in 1956 correspond to S1c in 2011). Overall, the sandy soils represented 63 % of the total watershed in 1956 and 60 % in 2011. Their hydrological properties are similar for the present and the past periods, except for crusted isolated dunes which represent 0.36 % of the total watershed in 2011 and were not detected in 1956.

Outcrops (O): Conversely, outcrops markedly developed in the northern part of the watershed. For instance, large areas in the northeastern part changed from pediment~~E1 sand sheets~~ to O2 outcrops. Overall, the surface of the outcrop classes has increased from 18 km^2 in 1956 to 27 km^2 in 2011.

Pediment (P):

~~***Erosion surface (E):***~~ Although the overall proportion of Pediment class (P)~~erosion surface unit (E)~~ on the watershed has not really changed between 1956 and 2011 (24% and 26% respectively), this unit underwent great~~the greatest~~ changes within the Pediment class.~~in terms of hydrological properties.~~ Indeed, all tiger bush units (P3)~~(E3)~~ have completely disappeared leaving impervious denudated~~and an important erosion of the underlying soil has occurred. Impervious bare~~ soils (P4),~~have replaced most of these areas,~~ sometime with ~~leaving~~ some rare trees or bushes, witnesses of the old tiger bush. ~~(E4).~~ In addition, the silt layer (P2) has increased from 7 km^2 to 11 km^2. The watershed map of 1956 also shows a large central area occupied by shallow sandy soils (P1v) that has completely disappeared and has been replaced by mostly impervious rocky Pediments (P1). This last landscape unit occupied 10 % of the total watershed in 1956 against 19 % in 2011.

These changes strongly impact the watershed hydrological properties, since P1 and P4 favor surface runoff compared to P1v and P3 (Table 3). In addition, the silt layer (P2)~~(E2)~~ has increased from 7 km^2 to 11 km^2, mainly in areas where the drainage network highly developed, reflecting the transition from sheet runoff to concentrated runoff and/or the increase of overland flow.~~. The watershed map of 1956 shows a large central area occupied by shallow sandy soils (E1v) that has completely disappeared and has been replaced by mostly impervious rocky erosion surfaces (E1). This last landscape unit occupied 10 % of the total watershed in 1956 against 19 % in 2011 and represents the major change that occurred over the watershed.~~

4.2 Model ~~calibration and~~ evaluation

The best agreement between observed and simulated annual discharges for the channel setup~~calibration~~ period is obtained with a channel Man~~MAN~~ of 0.03 s.m$^{-1/3}$ and a channel Ks~~KS~~ of 30 mm.hr^{-1} (Table 7), which is close to the best guess for these parameters.~~).~~ The corresponding bias is 2.7 % of the averaged discharge and the RMSE is equal to 6.4×10^5 ~~-~~m^3 (corresponding to 2.6 mm.yr^{-1} over the total watershed, ~~(~~n=5). As expected, several combinations of Man~~MAN~~ and Ks~~KS~~ give close results, higher Man~~MAN~~ compensating lower Ks.~~KS.~~ The optimized values of Man~~MAN~~ and Ks~~KS~~ correspond to rather impervious channels, which infiltrate much less than what is found in the literature for Sahelian watersheds, which reports a Man~~MAN~~ close to 0.03s.m$^{-1/3}$~~,0.03,~~ but a Ks~~KS~~ commonly reaching~~ranging from~~ 150 to 250 mm.hr^{-1}. These studies however concern particularly sandy areas where channels are several meters deep and are sometimes preferential infiltration sites (Chow, 1959; Estèves, 1995; Peugeot et al., 2007; Séguis et al., 2004). Conversely, the Agoufou watershed is characterized by ~~clayed and~~ silted very shallow soils or outcrops (northern part of the watershed) and silted channels ~~(southern part)~~ which is consistent with lower values of Ks.~~KS.~~

For the validation period (6 years with available observation during the period 2000 to 2010), the bias on the annual discharge is -1.2 % and the RMSE is 1.1×10^6 m^3 (4.5 mm.yr^{-1}; ~~(~~n=6) showing that the model performs reasonably well. For both the channel setup~~calibration~~ and validation periods, the inter-annual variability of the simulations is slightly greater than the observed one, with an under estimation for 2000-2001 (mid to low discharge years) and an over estimation for 2010 and 2013 (high discharge year, **Fig. 5**). The intra-annual variability of the simulated discharge is also reasonably close to the observations, considering the significant scatter of the simulated ensembles due the statistical rainfall disaggregation.

Overall, the annual cumulated discharge ~~for the validation and calibration periods~~ are close to the observations, with simulated mean annual discharges of 3.72×10^6 m^3 (15.2 mm.yr^{-1}; n=5) and 3.85×10^6 m^3 (15.7 mm.yr^{-1}; ~~(~~n=6) for the channel setup and ~~3.72×10^6 m^3 (n=5) for the~~ validation ~~and calibration~~ period respectively against 3.42×10^6 m^3 (14 mm.yr^{-1}; n=5) and 3.47×10^6 m^3 (14.1 mm.yr^{-1}; ~~(~~n=6) ~~and 3.42×10^6 m^3 (n=5)~~ for the observations. The mean relative bias between observed and simulated discharge during the whole period is 0.5 % (n=11) with a RMSE of 9.35×10^5 m^3 (3.8 mm.yr^{-1}; ~~(~~n=11).

4.3 Long term evolution and attribution of changes

4.3.1 Long term evolution

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~~For the past (1960-1975) and the present (2000-2015) simulations, the channels parameters retained are those obtained through the calibration process.~~ Results from the past and present periods are compared to all available observations of annual discharge (**Fig. 6**), namely 4 years for the past and 11 years for the present~~, and four years for the past.~~ Both observed and simulated ~~and observed~~ discharges showed an important increase over time, with a mean observed~~simulated~~ discharge of 0.02×10^6~~0.5×10^6~~ m^3 (0.08 mm.yr^{-1}; n=4) ~~(n=15)~~ and 3.43.10^6~~3.29×10^6~~ m^3 (14 mm.yr^{-1}; n=11)~~(n=15)~~ for the past and present periods respectively to be compared with 0.5×10^6~~0.02×10^6~~ m^3 (2 mm.yr^{-1}; n=15)~~(n=4)~~ and 3.29×10^6~~3.43.10^6~~ m^3 (13.4 mm.yr^{-1}; n=15)~~(n=11)~~ for the simulations. ~~observations.~~ For the past period, simulations overestimate the annual discharge for ~~all~~ the four years with observations. The observed~~simulated~~ runoff coefficient over the whole watershed (ratio between annual discharge and the precipitation over the total watershed area) is estimated at 0.02~~0.55~~ % (n=4)~~(n=15)~~ and 4.0~~3.87~~ % (n=11)~~(n=15)~~ for the past and the present periods respectively against 0.55~~0.02~~ % (n=15)~~(n=4)~~ and 3.87~~4.0~~ % (n=15)~~(n=11)~~ for the simulations.~~observations.~~

Despite the past simulations being overestimated and modeled variability being slightly larger than observed variability, both ~~simulations and~~ observations and simulations indicate a marked change in the watershed behavior between the past and present periods, with a discharge increase of an order of magnitude.

Precipitation during the present period averages 347 mm and displays a significant inter-annual variability, with extreme dry (2004, 2014) and wet years (2010, 2011). During the past period the precipitation average is equal to 382 mm, which is slightly above current value, and displays a smaller inter annual variability, in line with what is commonly observed in the Sahel (Lebel and Ali, 2009). The relation between event precipitation and discharge (**Fig. 7**) highlights important differences between the past and the present. First, for the same precipitation amount, the discharge is twice as large in the present as in the past. Second, for the present period, rainfall events larger than ~18.8 mm contribute to the discharge whereas in the past, rainfall events larger than ~30 mm were required.

4.3.2 Attribution of changes

Results from the K2 simulations outlined in Table 5~~Table 5~~ are summarized in **Fig. 8** and discussed in details below. The mean discharge (*mQ*) and the standard deviation (*Sd*) for each simulation are calculated for the ten members. The reference simulation corresponds to the simulation of the present case and the impact of the different factors tested by the different simulations is assessed through the *Ex values* (see Eq. 5).

Dune Crusting (C): This simulation corresponds to present characteristics without dune crusting. Replacing 30 % of the crusted dune area by dune without crusting has two effects on the land surface: first, soil Ks~~KS~~ increases (more infiltrability), and, second, the growth of herbaceous vegetation is made possible. These two effects favor infiltration and limit surface runoff generation. The overall effect of removing dune crust on the annual discharge is minor as it only explains **1 %** (*Ex*)~~ calculated using Eq. (4))~~ of the past to present evolution.

Drainage network Development (D): The present drainage network is replaced by the past network, meaning that the network development of the four sub-basins is deactivated and the contribution of the western part sub-watershed~~sub-basin~~ is forced to zero (by adding deep sandy channels that mimic the sand dunes barring the water flow). Overall, this factor explains **22 %** of the surface runoff increase over time. The western part of the watershed (Z1) is currently connected to the principal drainage network, and produces a runoff of 3.3×10^4 m^3 (0.1 $mm.yr^{-1}$) while the contribution of the network development over the Z2, Z3 and Z4 is equal to 3.6×10^5 m^3 (1.5 $mm.yr^{-1}$)~~,~~ 1.5×10^4 m^3 (0.06 $mm.yr^{-1}$) and~~—~~ 1.2×10^4 m^3 (0.05 $mm.yr^{-1}$) respectively. Overall, changes of the network drainage in the northern areas, where shallow soils and outcrops are found, have the largest impact on the simulated discharge.

Vegetation changes (V): This simulation tests the impact of the herbaceous vegetation expansion~~growth~~ on the annual discharge. It is implemented independently from soil type changes (see below), which is mostly academic since vegetation and soil type are most often tightly related. Nevertheless, such a simulation is useful for guiding for instance future model development and helps decipher the physical factors impacting runoff. For each plane,~~CSA,~~ the soil texture is kept at present values and the fraction occupied by herbaceous vegetation depends on the past maps (**Fig. 3a** and Table 4). This past map is characterized by the presence of shallow sandy soil (P1v)~~(E1v)~~ and deep sandy soils (S1, S2, S3 and S4), totaling 75 % of the watershed area, over which annual herbaceous plants can grow. The seasonal growth and inter-annual variability is forced by present day precipitations not to interfere with simulation "P".~~"P".~~ Vegetation efficiently slows surface runoff and increases infiltration capacity. As a result, simulation "V"~~"V"~~ produces a discharge of 2.1×10^6 m^3 (8.6 $mm.yr^{-1}$) and herbaceous vegetation changes explain **42 %** of the difference in surface runoff between past and present.

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Change in~~Modification of the~~ soil properties (S): This simulation tests the impact of soil changes~~modifications~~ on annual discharge without changing~~independently of~~ the herbaceous cover fraction, which is also an academic simulation. The fraction of all landscape units in each planes~~CSA~~ is defined by the past land cover map (**Fig. 3a**). The increase in some pediment units~~erosion surfaces~~ and outcrops over time~~,~~ results in a very strong impact on soil hydrological properties and then on the annual~~increase in surface~~ runoff. The simulation "S" produces a discharge of 0.67×10^{6} m^{3} (2.8 mm.yr^{-1}) and explains~~runoff, explaining~~ **95 %** of the change in annual discharge. Note that some landscape units, like tiger bush, comprise a fixed fraction of thickets, so that the simulation "S"~~"S"~~ accounts for changes in woody vegetation and thickets in addition to soil texture.

Precipitation (P): Precipitation impact is investigated by running K2 using past daily precipitations (1960-1975) and the watershed characteristics of the present period. As opposed to the previous attribution simulations, the simulation "P" produces a discharge of 4.09×10^{6} m^{3} (16.7 mm.yr^{-1}), or~~The result is~~ an increase of 0.8×10^{6}~~8.5×10^{5}~~ m^{3} (3.3 mm.yr^{-1}) compared with~~of~~ the present,~~discharge,~~ at odds with its observed reduction. This~~reduction, which~~ is an expected result since the precipitation average is slightly higher in the past period. Therefore, this factor results in a negative value of *Ex* (**-29 %**).

Crusting and Drainage network combination (CD): This simulation combines the first two attribution cases (dune crusting and drainage network development). The combination of these two factors explains only **23 %** of the difference of annual discharge between the two periods, which is equal to the sum of the two factors taken separately (1 % and 22 %).

Vegetation and Soil combination (VS): This simulation combines the effects of herbaceous vegetation map and soil type changes. Taken together, these two effects explain **101 %** of the difference in annual discharge between the two periods. The two factors do not impact runoff additively (101 % to be compared to 95 % plus 42 %), but are clearly strong enough to account for~~explain~~ the observed changes in the watershed outflow.~~behavior.~~

Crusting, Drainage network, Vegetation and Soil combination (CDVS): Last, this simulation combines four factors. It corresponds to the past case fed with the present precipitations. All these cumulated changes explain **105 %** of the difference of mean annual discharge between the two periods.

4.3.3 Spatial evolution over the watershed

The impact of landscape changes on the spatial distribution of Man and Ks within the watershed are presented in **Fig. 9a** and **Fig. 9b** respectively. Ks is predominantly related to the changes in the soil units while Man corresponds to the vegetation cover. The replacement of planes where shallow sandy soils dominated by planes with less pervious pediment units (see **Fig. 3**) led to important changes in Ks (**Fig. 9**). Planes subject to a decrease in vegetation cover display a decrease of the Man values (typically of the order of 0.1 s.m$^{-1/3}$ for the past period and smaller than 0.05 m.s$^{-1/3}$ for the present period). These local changes have induced an important and spectacular increase of the surface runoff generated over these planes (**Fig. 9c**): the contributing part of the watershed almost doubled with 20% of the watershed contributing in the past against 37% in the present period.

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4.4 Model robustness

The sensitivity analysis results are assessed by a comparison between the *Ex* values obtained by the attribution simulations for a reference case and the values obtained by the two sensitivity tests (Table 8) on planes and channels parameters. The reference case and the sensitivity tests are run using only one precipitation member, namely the closest to the ensemble average. This indeed leads to *Ex* values (Table 8, Column 3) very close to those reported for the attribution simulations on the 10 members ensemble (section 4.3.2). Regarding the first test, multiplying the Ks of all planes by 2.5 and Man by 1.75 decreases runoff by a factor of 3 (3.3 mm.yr^{-1} against initially 13.4 mm.yr^{-1} for the “PRES Ref” test), but it does not change the ranking of the different factors (Table 8, Column 3, 6 and 9), which is the primarily goal of these attribution simulations. The main difference in the *Ex* values is found for simulation “C”, with a more important contribution of dune crusting to the runoff increase, for planes with higher Ks and Man. The second sensitivity test uses Ks equal to 40 mm.hr^{-1} (which gives the lowest RMSE for the channel setup period) instead of 30 mm.hr^{-1} (which gives lowest bias). This results in a small decrease in total runoff in all simulations but it does not change the ranking of the different factors. The impact of the drainage network development is however sensibly lower than in the reference simulations, which is consistent with channels with higher infiltration capacity. Overall, these two sensitivity tests show the robustness of our results concerning the ranking of the different factors contributing to runoff changes between the past and the present. In particular, the impact of vegetation changes and the evolution of soils properties, which alone are sufficient to simulate the past-present difference, is a robust feature.

5 Discussion

5.1 Watershed evolution

The maps of landscape units were derived from different data (aerial photography and satellite images) of various spatial and spectral resolutions. Delimitation and identification of the landscape units proved easier for the present than for the past. Panchromatic aerial photographs give limited information and in many occasions the 3D visualization is necessary to clearly identify the units. Photo-interpretation for the past aimed to be conservative, meaning that obvious changes only were retained while ambiguous cases were considered as “no~~"no~~ change”.~~change".~~ Overall, despite the uncertainties related to the photo-interpretation and mapping of landscape units, that are not easily estimated, the land surface ~~condition~~ changes of the Agoufou watershed are important and clearly observable.

The results reported in **Fig. 3** highlight the increase in drainage density, which reaches a factor of 1.5 over the whole watershed and is accompanied by an expansion of open water surface (F2) and alluvial plains (F1). Similar changes were also observed by Massuel (2005) and by Leblanc et al. (2008) in southwestern Niger, where the drainage density increases by a factor of more than 2.5 between 1950 and 1992, as well as in a small watershed in northern Mali by Kergoat et al. (2015)~~(in prep)~~, who reported a factor of 2.8 between 1956 and 2008. Considering that few changes are observed on the southern sandy part of the basin, the evolution of the drainage network for Agoufou is consistent with the values found in the literature.

Woody vegetation, and especially the thickets of the tiger bush unit, and some of the shallow sandy soils have completely disappeared and have been replaced by hard pan outcrops and silt surfaces which is consistent with several studies (Hiernaux and Gérard, 1999; Leblanc et al., 2007; Touré et al., 2010; Trichon et al., 2012).

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Hiernaux et al. (2009b) have observed that the woody vegetation of the Gourma region has declined since the 1950s and particularly from 1975 to 1992 over shallow soils. Given that tiger bush thickets grow perpendicularly to the water flow and therefore protect the soil against erosion, capture runoff, and favor infiltration (Valentin et al., 1999 among others), disruption of thickets favors erosion, runoff concentration, and changes the overall hydrological properties. Sighomnou et al. (2013) in Niger have also noted a significant decrease of vegetation over shallow soils and a corresponding increase in denudated surfaces. In a watershed in Niger, Touré et al. (2010) estimated that the tiger bush occupied 69 % in the 70s and has disappeared in the 2000s. Man-driven deforestation has been put forward as a cause for thickets clearing in southwestern Niger. For Agoufou, such activity is not reported and remains of dead trees can be observed, testifying natural death of vegetation.

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The decay of shallow soil vegetation is not at odd with the Sahelian regreening that is observed all over the Sahel and in the Gourma since the 80s~~ ~~(Anyamba et al., 2003; Dardel et al., 2014a, 2014b; Heumann et al., 2007; Olsson et al., 2005). Dardel et al (2014b) suggest that the resilience of herbaceous vegetation allows rapid regrowth over most soils in response to rainfall recovery, but that a fraction of the shallow soils may undergo long term vegetation decay, in a way that impacts runoff but not region-average greening. In the Agoufou watershed, the vegetation changes affecting the northern part of the watershed would not be easily detected by coarse resolution satellite datasets, as opposed to the herbaceous vegetation growing over the sandy soils of the southern part of the watershed. In addition, the greening trend is obvious since the 80s, because of the maximal drought of 83 and 84, but the longer term trend is likely to be different (e.g. Pierre et al., 2016).

As far as land use change is concerned, a few additional enclosures (made of dead-wood fences whose prime function is to delineate land rights)~~In addition, the greening trend is obvious since the 80s, because of the maximal drought of 83 and 84, but the longer term trend is likely to be different (e.g. Pierre et al. 2016). As far as land use change is concerned, a few additional enclosures~~ are present nowadays in the Agoufou watershed, as a result of an easier access to water year-round since the lake became permanent. Located on deep sandy soils not contributing sensibly to runoff, these enclosures do not impact the overall characteristics of the watershed. ~~Indeed, they are dead-wood fences whose prime function is to delineate land rights.~~ In that respect, Agoufou differs from most of the watersheds studied in the Sahel so far (Niger, Burkina-Faso).

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5.2 A significant discharge increase despite the simulation limitation

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If simulations and observations are in good agreement for the present period, simulated discharge for the past period is overestimated (0.51×10^6~~(0.51.10^6~~ m^3 and 0.02×10^6~~0.02.10^6~~ m^3 for simulation and observation respectively or 2.1 $mm.yr^{-1}$ and 0.08 $mm.yr^{-1}$).~~).~~ Different reasons could explain this. First,~~this: first,~~ the error bars in **Fig. 8**, which represent the standard deviation of the ten members used for the ensemble simulations, illustrate the high sensitivity of the model to precipitation intensity. Moreover, the intra-annual dynamics (**Fig. 6**) also reflects the sensitivity of the model to a limited number of rainfall events each year. By assumption, the 5M rainfall intensity is supposed to be the same (i.e. to have the same distribution) for the past and the present periods. Lower 5M intensities in the past than in the present could then lead to lower simulated discharge values which could come closer to observations. However, there is no evidence of changes in precipitation intensity at this short time-scale (Panthou et al., 2014). Second, the model was evaluated~~calibrated and validated~~ with all available observation data over the 2000−2015~~2000-2015~~ period, when data are the most accurate and numerous.

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During the past period, only few data are available (four years) and the estimation of the annual discharge is less precise (see Gal et al., 2016) which could also account for part of the discrepancies between simulated and observed mean discharge in the past.

Moreover, all~~Moreover, model calibration was performed on the Manning's roughness coefficient (MAN) and saturated hydraulic conductivity (KS) of the channels. All~~ channels were considered to have the same characteristics over time and space but field observations suggest that the channels properties vary according to their geographical position, channels being possibly more permeable in the southern part than in the northern part, where they are also shallower. In addition, increasing surface runoff over time contributed to erode the soil surface and to increase sediments transport along channels downstream. If the sediment texture were mostly clay and silt, channels may have become more impervious, thus increasing runoff at the outlet. Less impervious channels in the past may therefore explain model overestimation. However, literature reports the reverse situation in the Sahel (Séguis et al., 2002) with materiel particularly rich in sand being transported. As for gully depth and soils, it is not clear whether the different Sahelian watersheds are comparable, given the importance of shallow soils and silt in the northern part of the Agoufou watershed.

Despite the possible sources of uncertainty previously identified, the difference between observations and simulations (0.14×10^6 and 0.49×10^6 or 0.5 $mm.yr^{-1}$ and 2 $mm.yr^{-1}$)~~)~~ is largely below the difference between the past and the present period (3.41×10^6 and 2.78×10^6 for the observation and simulation discharge respectively or 13.9 $mm.yr^{-1}$ and 11.3 $mm.yr^{-1}$, see **Fig. 7**).~~ ~~Simulated mean discharges for the present and the past periods are significantly different (t-test for means equality)~~ ~~as it is the case for observations (Gal et al., 2016).

5.3 Attribution of the Sahelian paradox

Changes in vegetation and soil properties alone are sufficient to simulate~~largely explain~~ the observed increase in watershed runoff over time. Previous studies of Sahelian hydrology agree on the major role of surface conditions on erosion and runoff generation (Casenave and Valentin, 1990; D'Herbès and Valentin, 1997; HilleRisLambers et al., 2001; Peugeot et al., 1997; Rietkerk et al., 2002). For the Agoufou watershed, the comparison of past and present land cover maps indicates that vegetation, mainly the dense thickets but more generally vegetation growing on shallow soils, has decayed after the severe droughts in 1972-73 and again in 1983-84 (Dardel et al., 2014b; Hiernaux et al., 2009b).~~For the Agoufou watershed, the comparison of past and present land cover maps indicates that vegetation, mainly the dense thickets but more generally vegetation growing on shallow soils, has degcayded after the severe droughts in 1972-73 and again in 1983-84.~~ The lack of vegetation recovery during the long drought period combined to erosion of shallow soils and runoff shift from sheet runoff to concentrated runoff is in agreement with findings by Séguis et al. (2004) who estimated, using hydrological modeling, that changes in land cover on the Wankama watershed, had multiplied the mean annual runoff by a factor close to three for the 1950–1992 period. Valentin et al. (2004) have also shown that a general decrease in vegetation cover modified the hydraulic properties of the topsoil and led to an increase in Hortonian runoff collected in numerous gullies and ponds. Our study highlights the predominant role of land cover changes in a pastoral area as opposed to several studies conducted in cropland dominated areas, which pointed to the leading role of the land use changes on surface runoff changes (Albergel, 1987; Favreau et al., 2009; Leblanc et al., 2008; Mahé et al., 2005).

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The drainage network development is a key marker of ecosystem degradation and more specifically of soil erosion (Descroix and Diedhiou, 2012; San Emeterio et al., 2013). However, studies of the direct impact of this phenomenon on surface runoff are scarce. Our study implieswork has shown that enhanced and concentrated runoff and/or increase surface runoff results in an increase in both the number and the length of channels, therefore increasing the drainage density and diminishing the travel time for water to reach the drainage network. This effect was also reported by Leblanc et al. (2008) in Niger.

Crusts are frequently cited as a possible explanation of the Sahelian paradox (Favreau et al., 2009; Leblanc et al., 2008; Mahé and Paturel, 2009). Our results suggest thatshow that the impact of crusted sandy dune on the surface runoff is limited.quite small. This is not necessarily the case further south like in southwestern Niger, where some soils have a higher percentage of clay. Moreover, soil crusting in the Agoufou landscape may be slightly underestimated given the low resolution of aerial photographs in 1956. Trampling by livestock, not considered here, has an unclear impact on soil crusting: according to the work by Hiernaux et al. (1999) on sandy soils in Niger, the soil infiltration capacity slightly increases with moderate grazing, but decreases at higher stocking rates. Moreover, the evolution of the stocking rates is poorly known over 1956-2011, although an increase cannot be excluded. Besides, it should be noted that in the literature, vegetation degradation is sometimes classified as "increase in surface crusting", while in this study changes from tiger bush vegetation into impervious soil, which are crusted, are simulatedconsidered as part of vegetation and soil changes ("VS" simulation).("VS" test).

Finally, the increase in the occurrence of extreme rainy events in daily precipitation suggested by Frappart et al. (2009) and demonstrated by Panthou et al. (2012, 2014) is intrinsically taken into account by the use of daily precipitation series used to force the model in our study. The results suggestshow that changes in daily precipitation regime do not explain runoff changes between the past and the present. If this variable is only taken into account (simulation "P"), simulated"P"), surface runoff decreasesis shown to decrease rather than increasingincrease over time. This is in line with Descroix et al. (2012), Cassé et al. (2015) and Aich et al. (2015), who found that the modest increase in large rainfall amount (events > 40 mm) observed during the 2000s cannot alone explain the Sahelian paradox. However, this should be taken with caution because changes in precipitation not statistically detectable here may have occurred elsewhere, due to the high natural variability, and further studies are required to address this question into more details.However, the question of rainfall intensification at a smaller time scale is still open, with no study being currently available to validate or invalidate this hypothesis for the Sahel.

6 Conclusions

In this study, a modeling approach was applied to investigateunderstand the paradoxical evolution of surface hydrology in the Sahel since the 60s. Landscape changes between 1956 and 2011 over the Agoufou watershed display four major features: 1) a partial crusting of isolated dunes, 2) an increase of drainage network density, with the connection of the western part of the watershed, 3) a marked evolution of the vegetation with the non-recovery of tiger bush and vegetation growing on shallow soils after the drought, 4) a marked evolution of soil properties with shallow soils being eroded and being replaced bygiving place to impervious soils (hard pans, outcrops or silt flats).

These changes were implemented independently and in combination in the KINematic EROSion model (K2) to quantify and rank their impact on mean annual discharge. According to the model, changes in~~Evolution of~~ soil properties and vegetation (grassland and tiger bush thickets) are large enough to reproduce~~largely explained~~ the increase of surface runoff observed between the past (1960–1975)~~(1960-1975)~~ and the present period (2000–2015),~~(2000-2015),~~ with the drainage network density also contributing to this effect. The non-~~-~~recovery of vegetation (woody and herbaceous) growing on shallow soils and soil erosion resulted in enhanced runoff, erosion, and drainage network development, in turn depriving vegetation from nutrient and water resources. According to our modeling results, these~~These~~ synergistic processes drive~~explain~~ the Sahelian paradox in the absence of land use changes.

The results reported here provide new perspectives towards better understanding the Sahelian paradox through hydrological modeling. Our study points~~point~~ out the need of taking into account all these processes in models aiming at representing hydrological past, present and future evolution in this region. In addition, the important landscape changes observed in this area highlight the interest of long-term monitoring of vegetation and hydrological variables in this region at a fine spatial and temporal scale.~~.~~

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~~6.1.1.1.1~~*Datasets*	~~6.1.1.1.2~~*Type*	~~6.1.1.1.3~~*Acquisition date*	~~6.1.1.1.4~~*Sources*
~~6.1.1.1.5~~DEM	~~6.1.1.1.6~~ RTM (30 m)	~~6.1.1.1.7~~ 23 September 2014	~~6.1.1.1.8~~ NASA
~~6.1.1.1.9~~Satellite images and aerial photographs	~~6.1.1.1.10~~ POT (5m)	~~6.1.1.1.11~~ 19 March 2004	~~6.1.1.1.12~~ CNES through Google Earth
	GeoEye-1	7 February 2011	DigitalGlobe through Google Earth
	Aerial photographs	November 1956	IGM: Instititut Géographique du Mali
Water outflow from the Agoufou watershed	Annual and intra annual	1965, 1966, 1973, 1975, 1984, 1990, 2000-2002, 2007, 2009-2015	Gal et al., 2016
Precipitation data	Daily	1920-2015	Hombori (Mali), Direction Nationale de la Météorologie, (DNM) and AMMA-CATCH
	5 min	2006-2010	Bangui mallam, Bilantao, Agoufou, Belia, Taylallelt, Nessouma, Hombori automatic raingauges (AMMA-CATCH network)

Table 1: Data available for the Agoufou watershed <u>and used in input K2 model.</u>

Sandy soils (S)	**S1:** Isolated dunes	Oval shaped isolated dune, often elongated in the direction of the prevailing northeasterly winds. Soil deflation and crusting may occurs creating patches prone to runoff (**S1c**).
	S2: Dunes system	Large sandy areas with succession of dunes and inter-dunes where the soil is deeper than 200 cm and has a very high infiltration capacity.
	S3: Deep sandy soil over bedrock	Sandy sheets typically 30 to 200 cm deep topping bedrock. Hydrological characteristics are close to those of the dune systems (S2) as the soil retention capacity is seldom exceeded.
~~6.1.2~~	**S4:** Enclosures	Enclosures sometimes cropped with millet located on sandy soil near water reaches. Hydrodynamic characteristics are close to those of the dune systems although land use is different.

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Outcrops (O)	**O1**: Rocky outcrops	Rocky outcrops correspond to schist or sandstone and are mostly devoid of vegetation. Infiltration is limited and most rainfall runs off. See also P1.~~E1.~~
~~6.1.3~~	**O2**: Hard pan outcrop	Hard pan outcrop largely devoid of vegetation. Infiltration is very low. See also P1.~~E1.~~
Pediments (P)~~Erosion surfaces (E)~~	**P1:** ~~E1:~~ Rocky Pediments~~erosion surfaces~~	These Pediments~~erosion surfaces~~ (or "glacis") combine hard pan outcrops and rocky outcrops interspersed with shallow sand-loam bars and sand-silt linear shaped deposits. They are the consequence of water and wind erosion and deposition responsible for deflation and silting and they produce important runoff except where shallow sandy soils (< 30 cm) are dominant. In this case, an herbaceous vegetation layer may be present **(P1v).~~(E1v).~~**
	P2: ~~E2:~~ Silt layer	These Pediments~~erosion surfaces~~ consist of a silt-clayed texture layer typically 30 to 100 cm deep laying on bedrock or hard pan, probably resulting from peri-desert silt. These soils are largely impervious and are a privileged area of runoff.
	P3: ~~E3:~~ Hard pan surface with tiger bush	Succession of bare surfaces and linear thickets made of a dense shrub population and a sparse herbaceous layer. This vegetation is often called “tiger bush”. Thickets are perpendicular to the slope and stop the runoff from the upstream bare patch. Banded vegetation grows on sandy-loam soil. The hydrological properties of the bare surface between thickets are those of impervious soils whereas thickets areas have high infiltration capacity. When not degraded, tiger bush systems produce little runoff (downstream) overall.
~~6.1.4~~	**P4:** P3~~E4:~~ ~~E3~~ eroded	Degradation of the tiger bush results in eroded and crusted soils which are largely impervious and produce important surface runoff. Traces of past woody vegetation can be observed (isolated thickets, dead logs).
Flooded zones (F)	**F1:** Alluvial plains	Floodplains are inundated during the largest rainfall events. This unit is characterized by alluvial sandy-loam or silty-clay soils. Large trees commonly grow along the channels.
	F2: Open Water	Ponds formed in depressions during the rainy season and permanent lakes (Agoufou lake in the study area).

Table 2: Characteristics of the landscape units (soil and land cover type, and hydrological properties).

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Infiltration (- to +)	Landscape units	Ks~~KS~~	G	DIST	POR	FR (S-S-C)	THICK	SMAX
		$mm.hr^{-1}$ ~~mm/hr~~	mm	-	cm^3/cm^3	%	mm	%
-	O1-O2-P1-S1c~~O1-O2-E1-S1c~~	0	0	0	0	0-0-0	n/a	0
	P2~~E2~~	5.82	224.2	0.38	0.414	5-17-28	n/a	86
	P4-F1~~E4-F1~~	11.82	108	0.25	0.463	36-41-22	n/a	94
	P1v -P3~~E1v -E3~~	142.98	83.2	0.59	0.435	80-9-11	300	96
+	S1-S2-S3-S4	192.13	46	0.69	0.437	92-3-5	n/a	96

Table 3: Summary of hydrological parameters for each landscape unit, sorted by increasing infiltration (Ks:~~(KS:~~ saturated hydraulic conductivity, POR: soil porosity, G: capillary charge saturation, DIST: pore distribution, FR: fraction of sand, silt and clay, and THICK: upper soil thickness).

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code	Vegetation type	Landscape unit	Man ($s/m^{1/3}$)~~MAN (-)~~	CC (%)	Ksnew~~KSnew~~ (mm/hr)
GT	Grassland + Trees	S1-S2-S3-S4	0.008*CCd	CCd	$Ks.e^{(0.0105*CCd)}$~~$KS.e^{(0.0105*CCd)}$~~
G	Grassland	P1v~~E1v~~	0.008*CCs	CCs	$Ks.e^{(0.0105*CCs)}$~~$KS.e^{(0.0105*CCs)}$~~
T	Sparse trees	P4~~E4~~	0.05	3	$Ks.e^{0.0315}$~~$KS.e^{0.0315}$~~
TB	Tiger bush thickets	P3~~E3~~	0.6	30	$Ks.e^{0.315}$~~$KS.e^{0.315}$~~
W	Woody plant	F1	0.05	20	$Ks.e^{0.21}$~~$KS.e^{0.21}$~~
R	No vegetation	O1-O2-P1-P2-S1c~~O1-O2-E1-E2-S1c~~	0.001	0	0

Table 4: Summary of the different land cover types and their hydrological parameters (Man:~~(MAN:~~ Manning's roughness coefficient, CC: canopy cover and Ksnew:~~KSnew:~~ saturated hydraulic conductivity modified).

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Simulations	Crusted dune	Drainage Network	Vegetation	Soil	Precipitations
PRESPresent	Present	Present	Present	Present	Present
C (Crusted dunes)	Past	Present	Present	Present	Present
D (Drainage network)	Present	Past	Present	Present	Present
V (Vegetation)	Present	Present	Past	Present	Present
S (Soil)	Present	Present	Present	Past	Present
P (Precipitation)	Present	Present	Present	Present	Past
CD	Past	Past	Present	Present	Present
VS	Present	Present	Past	Past	Present
CDVS	Past	Past	Past	Past	Present
PASTPast	Past	Past	Past	Past	Past

Table 5: Description of the simulations (1st column) and associated forcing (2nd to 5th column) for: the crusted dunes, the development of the drainage network, the evolution of the vegetation cover and soils and the change inmodification of the daily precipitation regime.

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~~7~~ Zones	~~8~~ Area (km²)	~~9~~ Total network length (km) ~~10~~ 1956	2011	~~11~~ Increase factor
~~12~~ Z1	~~13~~ 20.72	~~14~~ 6.1	~~15~~ 17.3	~~16~~ 2.85
~~17~~ Z2	~~18~~ 30.17	~~19~~ 10.1	~~20~~ 23.4	~~21~~ 1.93
~~22~~ Z3	~~23~~ 12.48	~~24~~ 6.4	~~25~~ 11.1	~~26~~ 1.75
~~27~~ Z4	~~28~~ 3.5	~~29~~ 0.2	~~30~~ 3.4	~~31~~ 14.01

Table 6: For the four sub-watersheds,~~sub-basin,~~ area, total drainage network length in 1956 and 2011 and the factor of increase between these two periods~~,~~ are given.

Bias (%) RMSE (mm.yr^{-1})	**Man (s.m$^{-1/3}$) 0.1**	**0. 2**	**0.3**	**0.4**	**0.5**
Ks (mm.hr^{-1}) 10	75.30 11.32	50.40 8.00	29.80 5.34	9.90 3.17	-9.20 2.54
20	60.00 9.26	33.80 5.85	14.10 3.54	-4.60 2.46	-22.10 3.49
30	48.40 7.71	21.80 4.36	2.70 2.61	-15.10 2.88	-31.30 4.50
40	38.90 6.47	12.10 3.32	-6.50 2.44	-23.60 3.65	-38.70 5.41
50	30.70 5.43	3.90 2.67	-14.20 2.80	-30.70 4.44	-44.90 6.20

Table 7: Percent bias and RMSE on annual discharge over 2011-2015 for 25 sets of channels Ks and Man parameters. The minimum value for the percent bias and RMSE is indicated by the square box (red and black respectively).

	Ref*			**S-PL****			**S-CH*****		
	mQ(10^{6}m^3)	**mQ(mm)**	***Ex* (%)**	**mQ(10^{6}m^3)**	**mQ(mm)**	***Ex* (%)**	**mQ(10^{6}m^3)**	**mQ(mm)**	***Ex* (%)**
PRES	3.3	13.4	0.0	0.8	3.3	0.0	3.0	12.3	0.0
C	3.2	13.3	2.7	0.7	2.8	14.9	3.0	12.2	1.0
D	2.7	10.9	22.1	0.7	2.7	19.6	2.8	11.4	8.9
V	2.1	8.7	41.9	0.3	1.3	63.7	1.9	7.9	43.3
S	0.7	2.6	94.0	0.1	0.2	97.2	0.5	2.2	98.1
P	4.1	16.7	-28.6	1.0	3.9	-21.5	3.7	15.3	-29.3

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PAST	0.5	2.1	100.0	0.0	0.1	100.0	0.5	2.0	120.0

*: Initial simulation with default parameters presented in **Fig.8**
**: Simulation with Ks (×2.5) and MAN (×1.75) modified for all planes
***: Simulation with Ks (40 mm.hr^{-1}) and MAN (0.03 s.m$^{-1/3}$) modified for all channels

Table 8: Mean annual discharge (mQ) and *Ex* values obtained for theinitial simulation with default parameters presented in Fig.8 (Ref*) and the sensitivity test for planes (S-PL) and channels (S-CH***) parameters.**

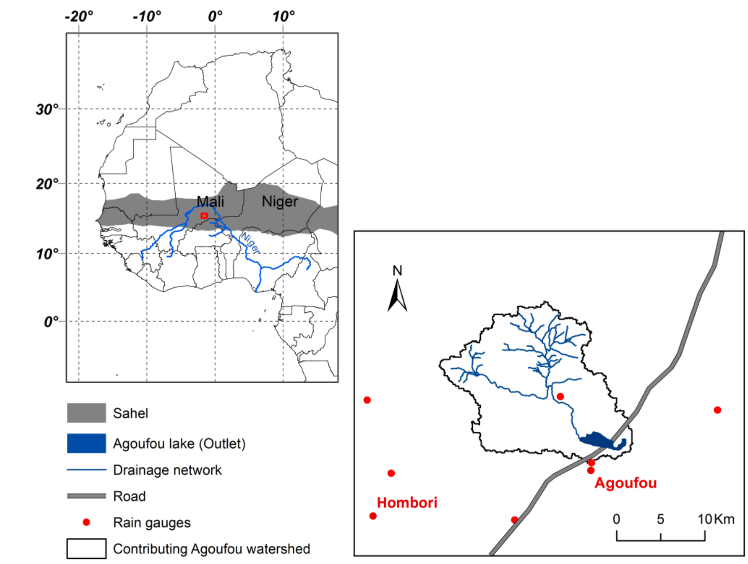

Fig. 1: The Agoufou watershed (245 km²) located in western Sahel (Mali) with drainage network and available rain gauges (map source: http://www.diva-gis.org/gdata).

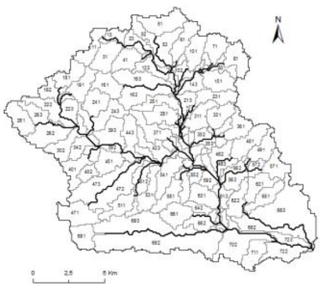

Fig. 2: Planes for the Agoufou watershed with the DEM-derived drainage network.

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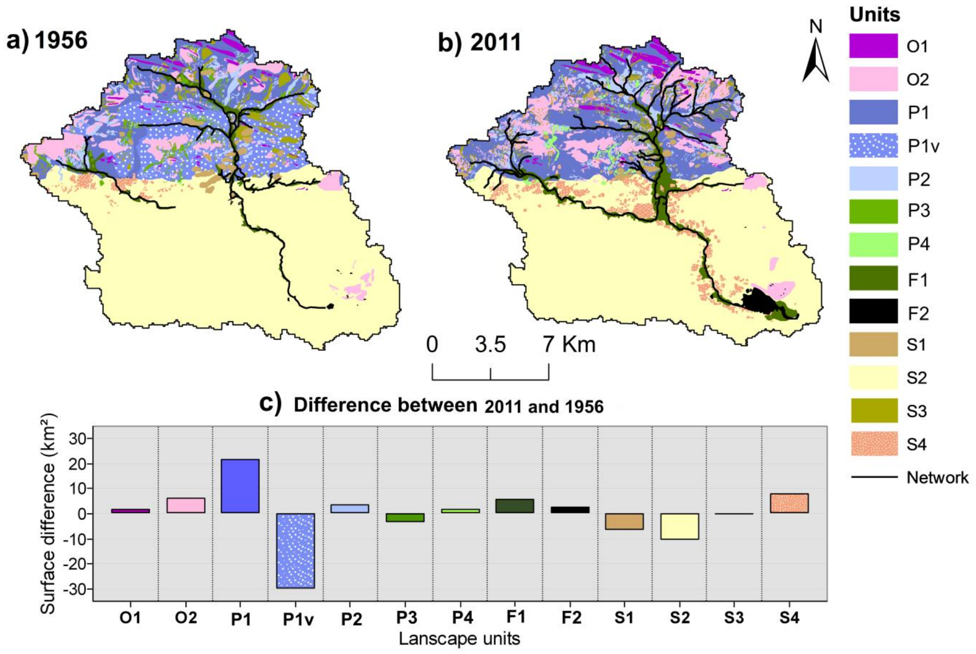

Fig. 3: Land cover maps of the Agoufou watershed for (a) 1956, (b) 2011 and (c) gives the surface difference (in km²) for each landscape unit, between 2011 and 1956.

Mis en forme : Police :10 pt, Non Gras, Non souligné, Couleur de police : Automatique

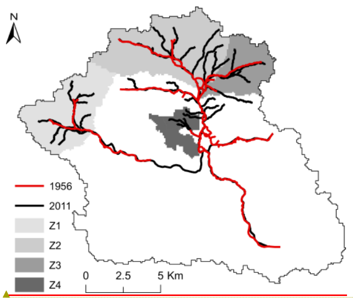

Fig. 4: Identification of the four sub-watersheds (grey shades) which display the largest changes between the drainage network in 1956 (red line) and in 2011 (black line).

Mis en forme : Police :10 pt, Non Gras, Non souligné, Couleur de police : Automatique

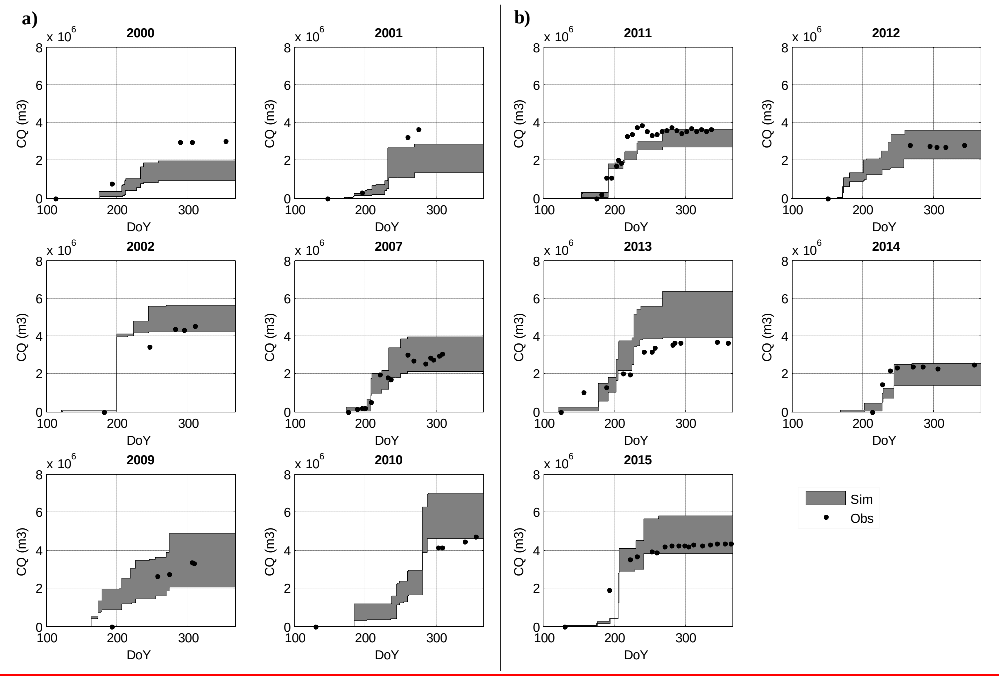

Fig. 5: Cumulative discharge (CQ) for years with observation data over 2000−2015. For each year, black dots are for the observations and the gray-shaded envelop represents the maximum and minimum of the ten members of the ensemble simulations. (a) is for the validation period and (b) is for the channel set-up period.

Mis en forme : Police :10 pt, Non Gras, Non souligné, Couleur de police : Automatique

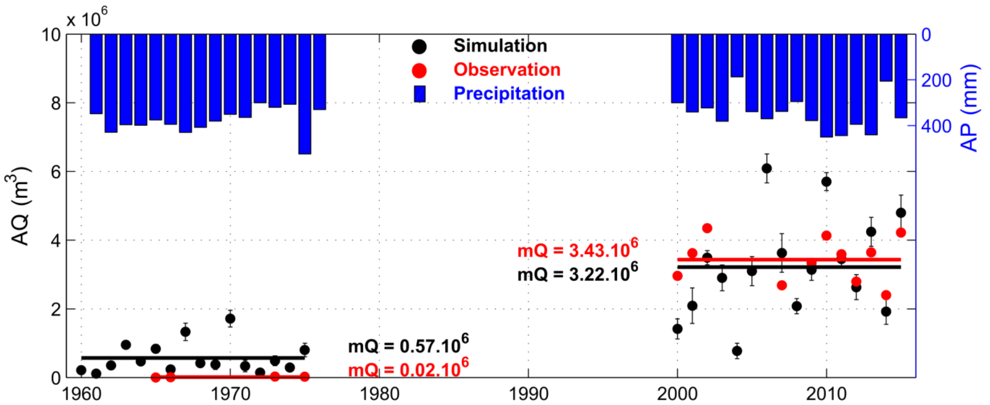

Fig. 6: Evolution of annual discharge (AQ in m3) between 1960 and 2015: simulations with standard deviation of the ten members (black dots with error bar) and observations (red dots) together with annual precipitation (AP in mm, blue bars).

Mis en forme : Police :10 pt, Non Gras, Non souligné, Couleur de police : Automatique

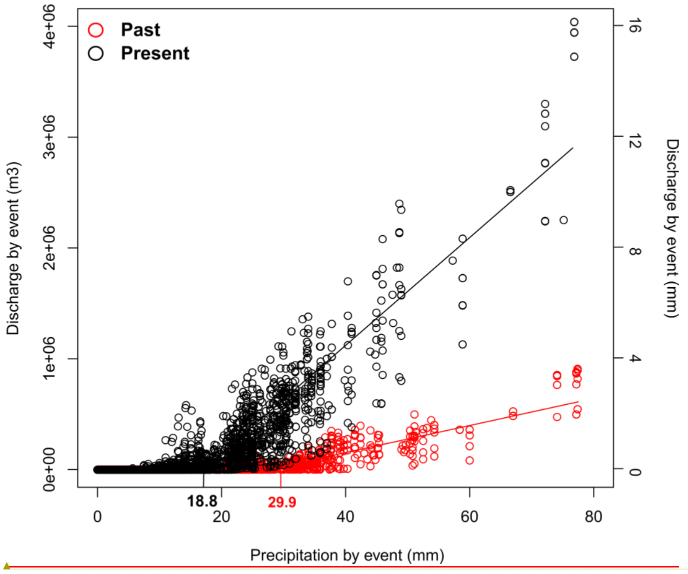

Fig. 7: Relation between precipitation and discharge for all events in the 15 years period in the past (red points) and the present (black points).

Mis en forme : Police :10 pt, Non Gras, Non souligné, Couleur de police : Automatique

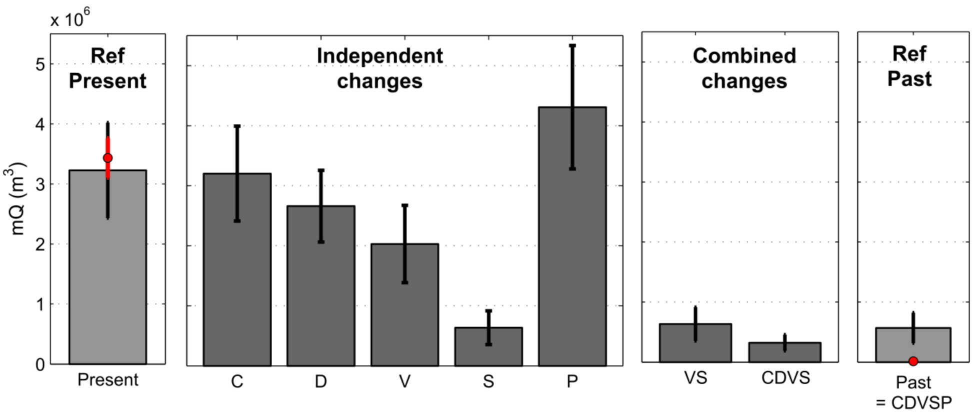

Fig. 8: Mean discharge (mQ) for present and past reference cases and for the attribution simulations described in Table 5, with either independent or combined factors. For the references cases, observation data are added (red points). Errors bars indicate the standard deviation of the ten member and the fifteen years of simulation.

Mis en forme : Non souligné, Couleur de police : Automatique

Mis en forme : Police :10 pt, Non Gras, Non souligné, Couleur de police : Automatique

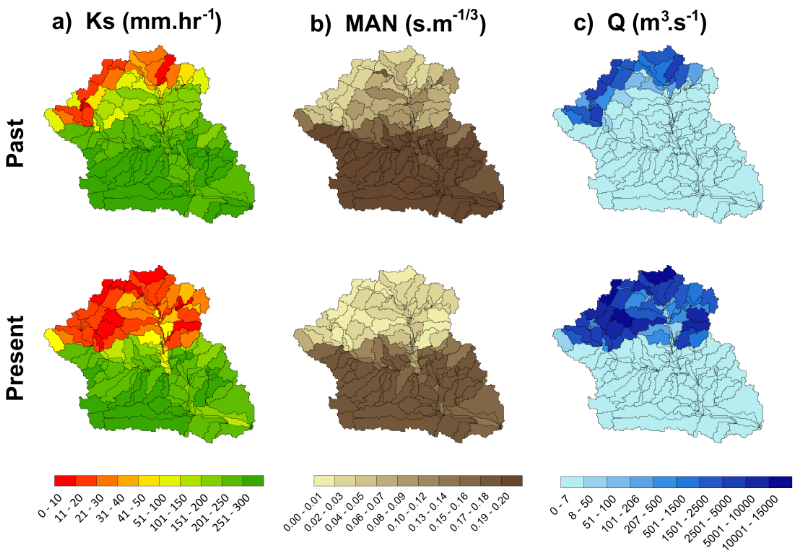

Fig. 9: Spatial patterns of the a) saturated hydraulic conductivity (Ks), b) Manning's roughness coefficient (Man) and c) Discharge (Q) between the past and the period for the monsoon season (JAS).

Mis en forme : Justifié, Espace Avant : 6 pt, Interligne : 1.5 ligne, Sans coupure de mots