

Responses to Referee #1

Dear Referee,

Thank you for your comments. We partially agree with referee #1 concerning the comments on the hypotheses, concepts, science questions and advancements in this paper. The scope of this paper is to develop a combined approach of data acquisition and the development of a new semi-distributed model taking into account land-use changes to reconstruct and predict annual runoff on a catchment exposed to high urban increase. As stated by referee #2, “*the research question is interesting, and the methods used in this study are well explained.*” However, we totally agree with all the other comments of referee #1 especially that some hypotheses and concepts of the model worth detailed analysis and comparison to classical well-known approaches in the literature. We agree with the main comments of both referees #1 and #2, and we propose to substantially modify the paper outline and add new sections taking into account all points raised by both referees.

We give in this letter our responses in blue.

For the authors

Camille Jourdan

Anonymous Referee #1

Received and published: 22 June 2019

“The paper develops a simple regression-based annual runoff model and evaluates the model’s performance in data sparse environments in Cameroon to assess the role of urbanization on runoff. The model uses and catchment index I, similar to the CN of the SCS-CN equation. The difference was that this index was designed for annual runoff.

I was not able to find any new hypotheses, concepts, science questions and advancements in this paper.”

We agree with referee #1 that the paper doesn’t put forward well the advancements and we would like to perform significant modifications in order to improve it. We want to emphasize that the main scientific question treated by the paper is about hydrological impacts of urbanisation in data-sparse region with the interest to present new data acquisition in tropical urbanized area. This paper also proposes a new parsimonious model leading to a satisfying back-casting of annual runoff at the catchment scale.

The first interest of our study is the data collected on the field for heterogeneous land-use basins from short-term instrumentation. Many papers assessed the impact of forest conversion into cropland on the hydrological cycle in tropical countries (Beck et al., 2013; Giertz et al., 2006; Yira et al., 2016), but very few studies treats the urbanization impacts in tropical zone from field observations due to the lack of data. The data presented in the paper at the annual scale are also available at hourly scale and enable to assess the impact of land-use changes on hydrology at several time scales. We propose to make additional analyses at the monthly and seasonal scales in order to improve this paper (see response to comments n°3 and n°4 of referee #2). The analysis at the finer hourly time step is treated in another paper in preparation.

The second interest is the use of historical sparse data to complete the instrumentation in order to have a maximum of information to validate the model. Most of the studies in tropical regions applied simple models to assess hydrological impacts of urbanization (Barron et al., 2013; Remondi et al., 2016) but few have the opportunities to confront simulations with real field observations.

The third interest is the model itself, using sparse data, easy-to-use by stakeholders, parsimonious and integrating land-use changes. The hydrological index I is a simple indicator taking into account land-use change using available remote sensing data.

“I’d would have appreciated if the authors at least used the Budyko framework or simple annual water models like the ABC model, both of which has more sound conceptual basis that involve water and energy.”

We agree that this new model must be compared to classical approaches such as the Budyko or simple conceptual models in order to show the advantages and the limitations of the new model we propose. We propose to add a special section to do this comparison: 1. The Budyko model; 2. The conceptual annual model GR1A (Mouelhi, 2003; Mouelhi et al., 2006) ; 3. The monthly GR2M model (Mouelhi, 2003) . These models have similar conceptual concepts as the ABC model.

1. The Budyko model

The Budyko model (Budyko, 1974) was applied at the annual data on: i) the available data at the Mefou basin at outlet at Nsimalen (catchment area 421 km²) and ii) for the donor catchments. We included in the analysis uncertainties on precipitation, potential evapotranspiration PET , and losses due to overbank flow at the outlet.

Figure R1.1 shows the results at the Méfou main outlet at Nsimalen. The green dark points correspond to years before 1980 with a low impact of urbanization. The light green points correspond to years after 2000 with a high impact of urbanization. We observe that for the period before 1970, points are very close to the energy limit; the estimated actual evapotranspiration AET is close to the estimated potential evapotranspiration PET . Then, points trends to go down over time. The value of AET/P (with P the annual precipitation) is about 0.75 for 1964-1967 and below 0.6 for 2005-2013. This first analysis confirms the impact of urbanization on the annual water balance at the whole catchment scale at Nsimalen.

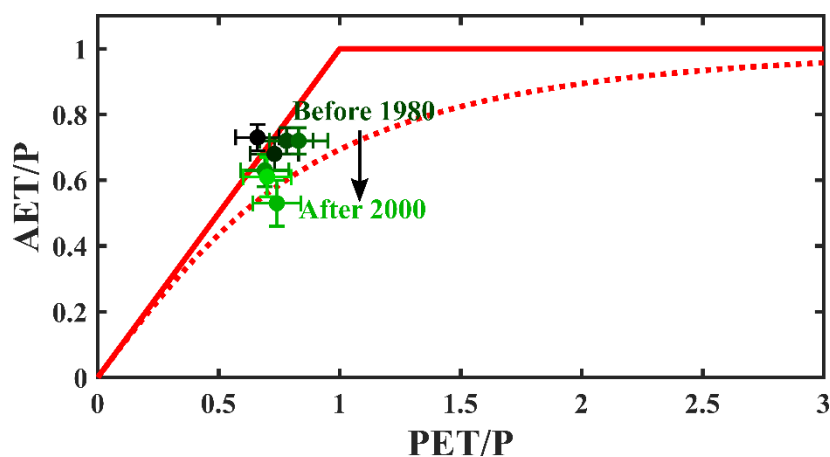


Figure R1.1. The Budyko model showing the relationship between the aridity index PET/P and AET/P for the available yearly data of the Mefou basin at outlet at Nsimalen (PET : annual potential evapotranspiration; P : annual precipitation; AET : actual evapotranspiration; with the hypothesis of a nil annual storage variation as discussed later in response to comment n°3 of referee #2). Green dark points correspond to the period before 1980 (low impact of urbanization) and light green to the period after 2000 (high impact of urbanization).

Figure R1.2 shows the results for the donor catchments. The dark blue points correspond to donors with low index I (low urbanization) and light blue to donors with high I (high urbanization). We

observe that points corresponding to catchments with low index I (i.e. land-use to natural conditions without urbanization) are close to the energy limit with AET/P around 0.75. More the index increases, more points trend to go down and move away from the energy limit with AET/P around 0.2. This relationship shows the high impact of the I index (which increases with urbanization) on the annual water balance.

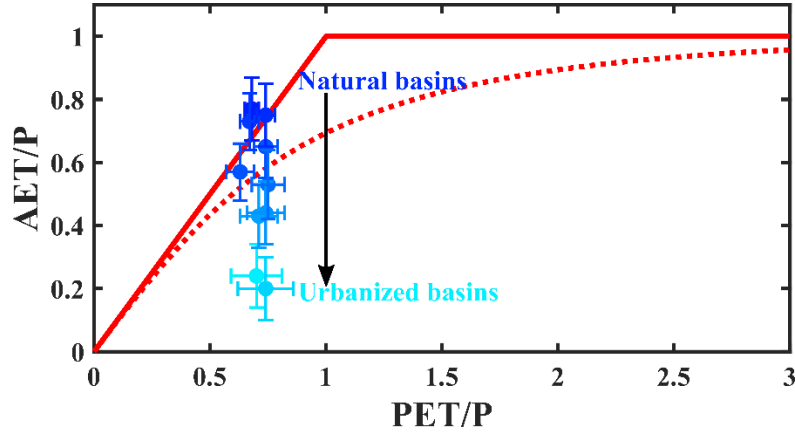


Figure R1.2. The Budyko model showing the relationship between the aridity index PET/P and AET/P for the donor catchments. Dark blue points correspond to donors with low I index (low urbanization) and light blue to donors with high I index (high urbanization).

We propose to add these results on a new section (see the suggested outline at the end of this response).

2. The annual GR1A model

We used the *GR1A* model to compare the model we developed to a classical standard annual hydrological model used in France (Figure 12). The *GR1A* is based on the Turc (1954) equations framework (Mouelhi, 2003). *GR1A* is defined by the equation R1.1.

$$R_k = P_k \left\{ 1 - \frac{1}{\left[1 + \left(\frac{0.7P_k + 0.3P_{k-1}}{X \cdot PET_k} \right)^2 \right]^{0.5}} \right\} \quad (R1.1)$$

with k the studied year, R the annual runoff, P the annual precipitation and PET the potential evaporation. The *GR1A* model has only one parameter X which is empirical and not easily linked to urbanization. Consequently, it is difficult to apply the model in changing environment conditions.

We carried on several calibration/validation tries of the model *GR1A* on the available database of the Mefou basin at outlet at Nsimalen (Table R1.1): i) calibration of X on the period 1964-1976 before urbanization and validation on the period 2005-2013 after urbanization; ii) similar as in i) but exchanging the periods of calibration and validation; iii) calibrating on odd years and validating on even years in order to obtain a mean value of X on periods impacted by urbanization. Figure R1.3 shows the different simulations.

Tableau R1.1. Summary of calibration tries for GR1A model at the Méfou outlet at Nsimalen.

Calibration Period	Calibrated X	Performance (RMSE in mm) Calibration period	Validation Period	Performance (RMSE in mm) Validation period	Total performance (RMSE)
1964 – 1976	1.15	91.0	2005 – 2013	170.1	144.0
2005 – 2013	0.90	152.7	1964 – 1976	215.0	146.0
Odd years over 1964-2013	1.05	123.4	Even years over 1964-2013	130.4	126.8

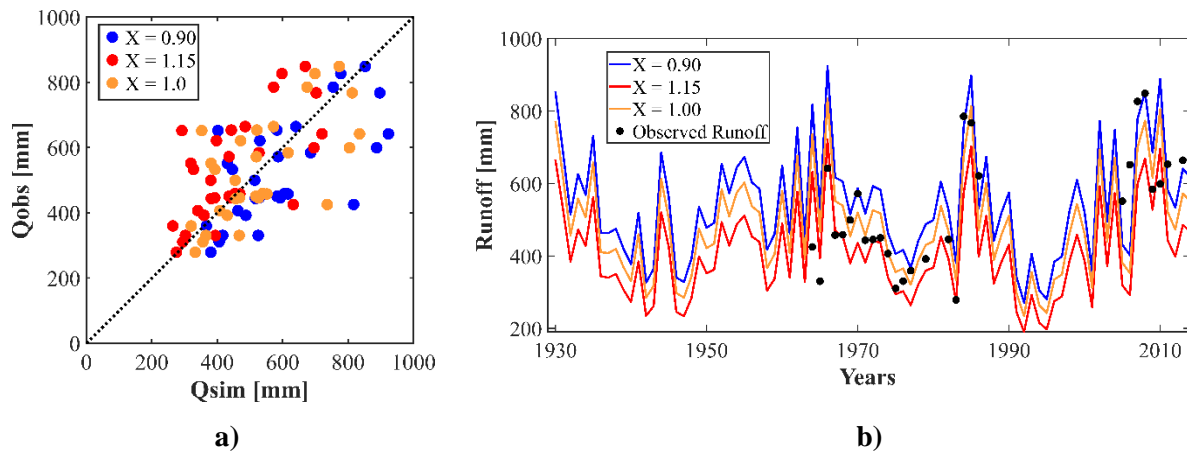


Figure R1.3. Simulated annual runoff from *GR1A* model for the three calibrated values of parameter X presented in Table R1.1. a) Presentation of simulated and observed annual runoff. b) Presentation of simulated annual runoff over the period 1930-2015.

We observe that the calibrated parameter X decreases from 1.15 (period 1964-1976) to 0.90 (period 2005-2013) mainly explained by changes in land-use characteristics. The performance of the *GR1A* (using the RMSE) decreases drastically when comparing the calibration and the validation periods for the two first tests. The last try is most satisfying with comparable values between calibration and validation performance, this try lets to use old and recent years in both calibration and validation steps; the calibrated value of the parameter X is about an average of the calibrated parameter of the two first calibration tries. In the Figure 12 of the paper, we present the last calibrated *GR1A* model. We observed that the calibrated *GR1A* model (third try) overestimates runoff of the oldest years and underestimates runoff of the most recent years. Figure R1.3 shows that the simulations of the *GR1A* model which presents difficulties to well simulate the annual runoff on the whole period because of changes in land-use.

We propose to add this analysis of data by the model *GR1A* in a new section in the revised version (see the suggested new outline at the end of this response).

3. The GR2M model

We also propose to add in the same section the using of the monthly model *GR2M* in order to show the low inter-annual water soil storage variation at Mefou at outlet at Nsimalen (see response to comment n°3 of referee #2)

We propose to add this analysis of data by the model *GR2M* in a new section in the revised version (see the suggested new outline at the end of this response).

I'm not convinced that this paper deserves publication in HESS. It looks like a nice project report.

We think that the topic of the impact of urbanization on water resources in regions with sparse-data as in Africa is of great interest for hydrological research and for stakeholders. The main difficulty states in the lack of data, and the need to develop special models adapted to the main hydrological processes, land-use change, and easy-to-use by stakeholders. The main originality and novelty of this work concerns:

- i) A new recent dense field experimentation especially adapted to measure rainfall/runoff on catchments with various land-use and a strong density of urbanization. Additional data from archives were also used.
- ii) An analysis of the main processes in order to build a parsimonious model adapted to the study site: a) low spatio-temporal rainfall variability: $P_n < P < P_x$; b) low inter-annual and annual *PET* variability; c) low variability of annual water soil storage. Use of the Budyko model, *GR2M*, *GRIA* in order to show the limits of the existing approaches (see details in the responses to referee #2)
- iii) The development of a model adapted to the previous constraints and comparison and tests of various formulations taking into account uncertainties on data.

For that, we propose to substantially modify the paper outline taking into account the points stated above. We suggest the new following outline

1. Introduction
2. The study site
3. What we learn from data
 - 3.1 Precipitation
 - 3.2 PET temporal analysis
 - 3.3 The Budyko model
 - 3.4 The annual *GRIA* and the monthly *GR2M* models
 - 3.5 Constraints for modelling
4. The annual rainfall-runoff model
 - 4.1 General model structure
 - 4.2 Sensitivity analysis and comparison of different formulations
5. The hydrological index
 - 5.1. The present model
 - 5.2. Comparison of different approaches taking into account AET, ΔS , and seasonality.
6. Applications
 - 6.1. The present model
 - 6.2. Comparison of different approaches of the model structure and the index I

In comparison to the original version, we propose to add sections and to reverse other sections:

First, the introduction will be substantially reinforced in order to show the main novelty and sciences questions of this work.

Second, the study site is presented (similar to the original paper)

Third, we propose to add a detailed data analysis section called “3. What we learn from data”. In this section, we keep the subsection on the spatio-temporal analysis of precipitation (noted 3.1). We propose to add four new subsections: 3.2 PET temporal analysis (see response to referee #2); 3.3. The Budyko model (see response to referee #1); 3.3. The annual GR1A model (see response to referee #1) and the GR2M model (see response to referee #2); 3.4. Constraints for modelling explaining the originalities of the new approach in comparison to classical ones (see responses to both referees #1 and #2)

Fourth, we propose to modify substantially the section concerning the model in order to show the hypotheses of the new approach (see response to referee #2) and to add a sensitivity analysis and a comparison between the different modelling approaches (see responses to referees #1 and #2).

In Sections 5 and 6, we propose to compare various structures of the model taking into account the model general equations, but also introducing potential evapotranspiration PET, inter-annual stock variation and seasonality (see details in the responses to referee #2).

The conclusion will be modified and adapted.

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