Supplementary Material

A non-stationary model for reconstruction of historical annual runoff on tropical catchments under increasing urbanization (Yaoundé, Cameroon)

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1 Introduction

The Supplementary Material gives additional information on data and model application, and is organized as follow: climate, land-use, review of annual runoff studies, monthly runoff and land-use relationships, sensitivity analysis of the model, and review of studies analyzing the impact of land-use changes on runoff in tropical and/or urban context.

2 Climate

Figure S1 presents the monthly precipitation, temperature and potential evaporation *PET* for the Yaoundé region. Precipitation and temperature were recorded at Mvan Airport (P_1. Fig. 3a) for the period 1951-2006 (Nguemou 2008). *PET* was estimated by Ikounga (1978) with two methods (Bac Colorado and bac Class "A") leading to the uncertainty range presented in grey.

3 Land-use

3.1 Pictures of the different land-uses

Figure S2 shows satellite images of heterogeneous conditions of urbanization. Figure S3 presents pictures of various conditions of land-use over the Mefou catchment: cropland (Figs. S3a, b), very urbanized areas (Figs. S3c, d), and some natural portions (Figs. S3e, f).

3.2 Yaoundé urban area extension 1930-2017

Different products were analyzed in order to visualize the evolution of Yaoundé urban extension over the Mefou catchment from 1956 to 2019 (Fig. 3b). Moffo (2017) analyzed historical serial of aerial photography of 1956, and we analyzed satellite images (Google Earth ®) of 1984, 1988, 2000, 2010 and 2019 and additional information from CUY (2008). Figure S4 shows the urban area extension obtained from aerial photography or satellite images: extension between 1960 and 1990, densification of urbanized area between 1990 and 2000, important extension of the city from 2000 to 2010, very important extension and densification of the urban area from 2010 to 2018.

3.3 Land-use changes 1930-2017

Tables S1 and S2 give the references and products used to quantify land-use changes and the proportion of urban area *U* on donors and targets catchments. Franqueville (1979) describes the city of Yaoundé in 1950.

The various products show a decrease of about 140 km² of forest cover over the Mefou catchment since 1980 (see forest cover losses since 2000, Figs. S5 and S6). Hansen et al. (2013) proposed a global high resolution (30 m x 30 m) product on whole Africa, showing on the Mefou catchment at Nsimalen (421 km²) losses in forest cover of 95 km² from 2000 to 2017 (Fig. S5). These results are similar to those obtained by Ebodé (2017) over the whole Mefou catchment at the outlet (802 km²). Figure S6 shows the losses per year between 2000 and 2017 which are particularly important after 2013 (estimated to more than 50 km²).

In the opposite, the urban area has grown from about 40 to about 160 km² over the same period (Figs. S7 and S8). Figure S7 shows the urban area extension between 1980 (38 km²) and 2001 (159 km²) of the Urban Community of Yaoundé (CUY, 2008). Figure S8 shows the urbanized area obtained from the maps of Midekisa et al. (2017) over Africa. The two studied periods 2000 and 2015, shows the huge development of urbanized areas (from 75 km² to 158 km²) and a decrease of high biomass surface (dense forest).

All these references and global products were used to calculate the percentage of urbanized areas *U* over each target catchments. Table S3 presents for 1930, 1950, 1980, 2000, and 2017 the values of *U*. The land-use component for the 8 targets for the 5 periods is then evaluated from *U* values.

4 Review of annual runoff studies over the Nyong and Mefou basin

Table S4 summarizes the main studies and information on the annual water balance over the Nyong sub-catchments from small (< 1 km²) to large scales (> 10,000 km²) since 1960. Figure S9 presents the location of hydrometric stations on the Nyong Basin (presented in Table S4 or from the dedicated short-term instrumentation). The majority of sub-catchments have natural land cover. The short-term instrumentation dedicated to the present study aims to complete this dataset with catchments characterized by different land-use conditions, mainly urbanized zones.

5 Monthly runoff and land-use relationship

Data from donor catchments (historical studies and short-term dedicated measurements) presented in the paper at the annual scale were also analyzed at the monthly scale (Fig. S10). We observe for D_{I2} and D_{I6} high differences in monthly runoff for these two catchments presenting similar values of urbanized area proportion *U* and similar precipitation values. For October, differences of runoff are important with 170 mm for D_{I2} against 93 mm for D_{I6} (Table S5). Differences in topography and soil conditions could explain part of runoff differences: D_{I2} is located in the upstream part of the Mefou basin with a slope index $S_I = 13.6\ \%$ higher than the slope of D_{I6} (S_I = 6.7 %) and an estimated proportion of hydromorphic soil $HS = 0\ \%$ much more lower than D_{I6} (HS = 24.0 %). Figure S10 shows a clear impact of land-use condition (illustrated by C_{LC}) over monthly runoff for the donor dataset: high values of C_{LC} (corresponding to high proportion of urbanization) correspond to high values of monthly runoff.

6 Sensitivity analysis of the model

When adjusting the linear regression $\rho = aI + b$, we make first a sensitivity analysis on land-use component weight ω_{LC} of the hydrological index I for different values of ω_{LC} = 3, 5, 7 and 10 (with $\omega_S = \omega_T = 1$). Table S6 shows the adjusted parameters (*a* and *b)*, the values of ρ for $I = 1$ and $I = 0.5$, and the determination coefficient r^2. We observe that for ω_{LC} = 5, 7 and 10, the impact on regression parameters is very low. Second, we studied the impact of different number of donor catchments on the model parameters. The set of donors retained always integrates donors with heterogeneous values of I (at least one catchment with $I < 0.3$ and at least one catchment with $I > 0.7$). Table S7 shows the range of the parameters *a* and *b* for a number of donors varying from 6 to 10 and the values of the performance criteria defined in Sect. 2.2. Results show a low sensitivity, especially when the number of donors exceeds 8.

7 Review of studies analysing land-use changes impact on annual runoff in tropical and/or urban context

In order to compare our results with other studies of land-uses changes impact at the annual scale in tropical and urban context, we did a review over the subject. Table S8 present studies of LULC changes impact in tropical and African context and Table S9 present study of urbanization impact on annual runoff or water balance components. Many studies quantified the impact of land-uses changes by modelling (Beck et al., 2013; Yira et al., 2013) due to poorly-gauged context in tropical region. Most of studies in tropical region analyzed the impact of cropland conversion or forest retreats/regeneration over annual runoff (Beck et al., 2013, Gessess et al., 2014) but few studies analyzed the urbanization impact on annual runoff and most of theme treats with temperate of Mediterranean climates.

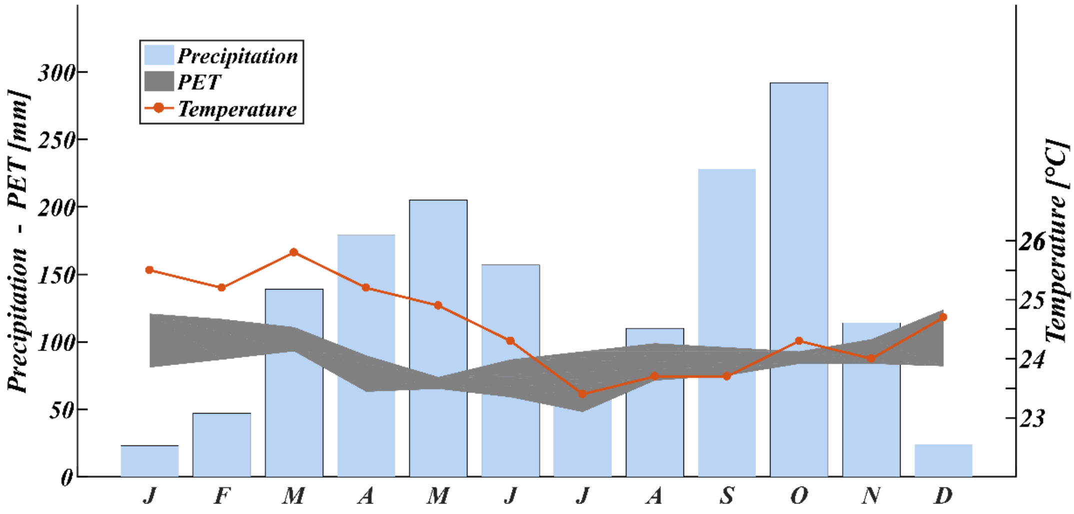


Figure S1. Mean monthly precipitation, temperature and *PET* for Yaoundé.

a.

b.

c.

d.

Figure S2. Satellite images of various land-use conditions over the Mefou catchment. a) Very urbanized portion of the catchment characterized by the highest values of C_{LC} (C_{LC} = 1) (Mfoundi Upstream). b) Very urbanized area with some natural portions (lowlands) (Mfoundi downstream, C_{LC} = 0.8); c) Intermediary condition of urbanization (Angaa portion, C_{LC} = 0.4); d) Very few urbanized portion (Mopfou upstream, C_{LC} = 0).

a.

b.

c.

d.

e.

f.

Figure S3. a) Cropland zone of the catchment (on target T_3); b) Cropland and forest (T_1); c) Very urbanized (T_5); d) Canalized river on the Mfoundi upstream (T_5); e and f) Downstream of the Mefou basin (T_4). The notation T_i refers to target catchments in Fig. 4b.

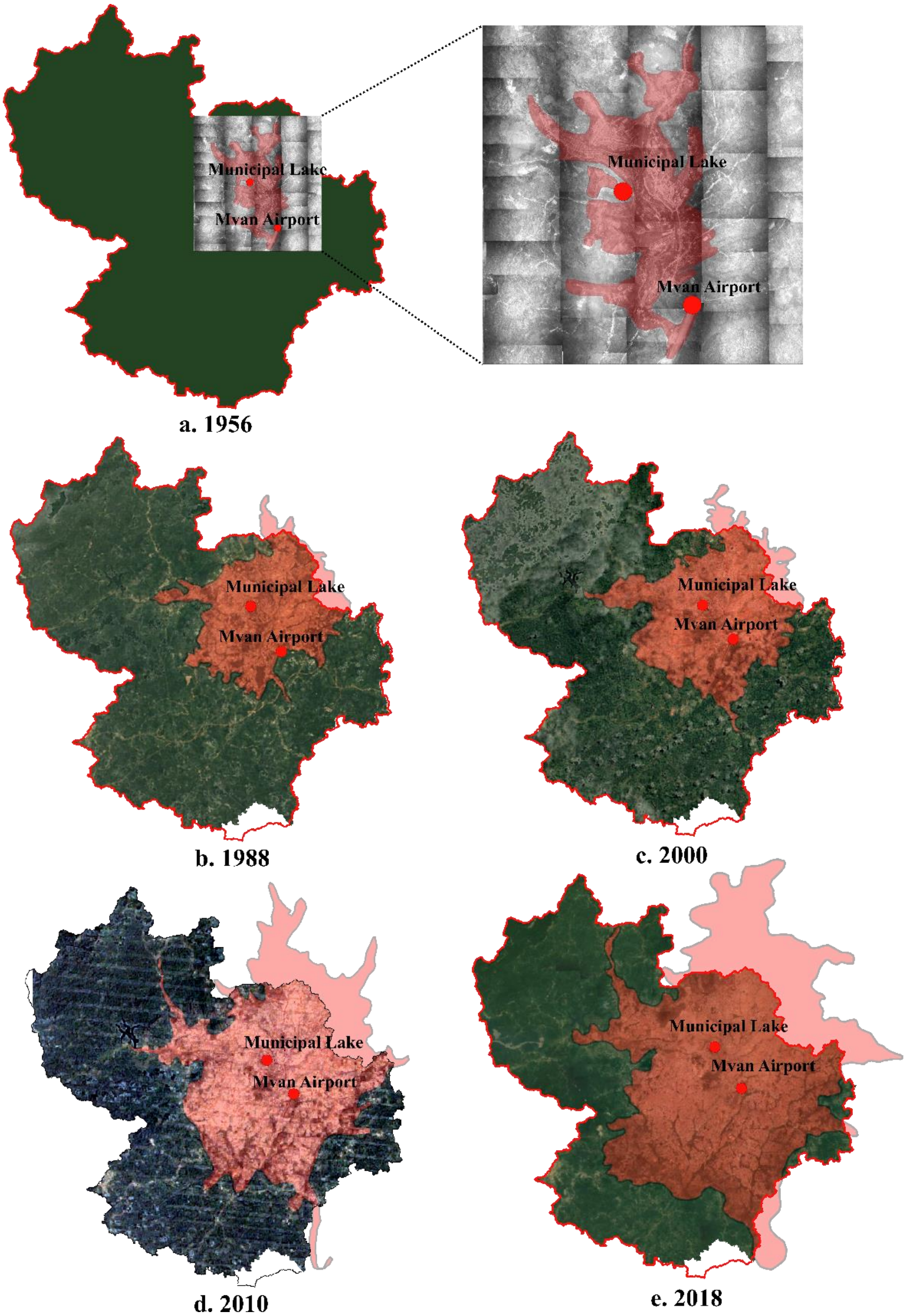


Figure S4. Urban area extension in 1956 (aerial photography from Moffo, 2017), 1988, 2000, and 2018 (Satellite images ®GoogleEarth).

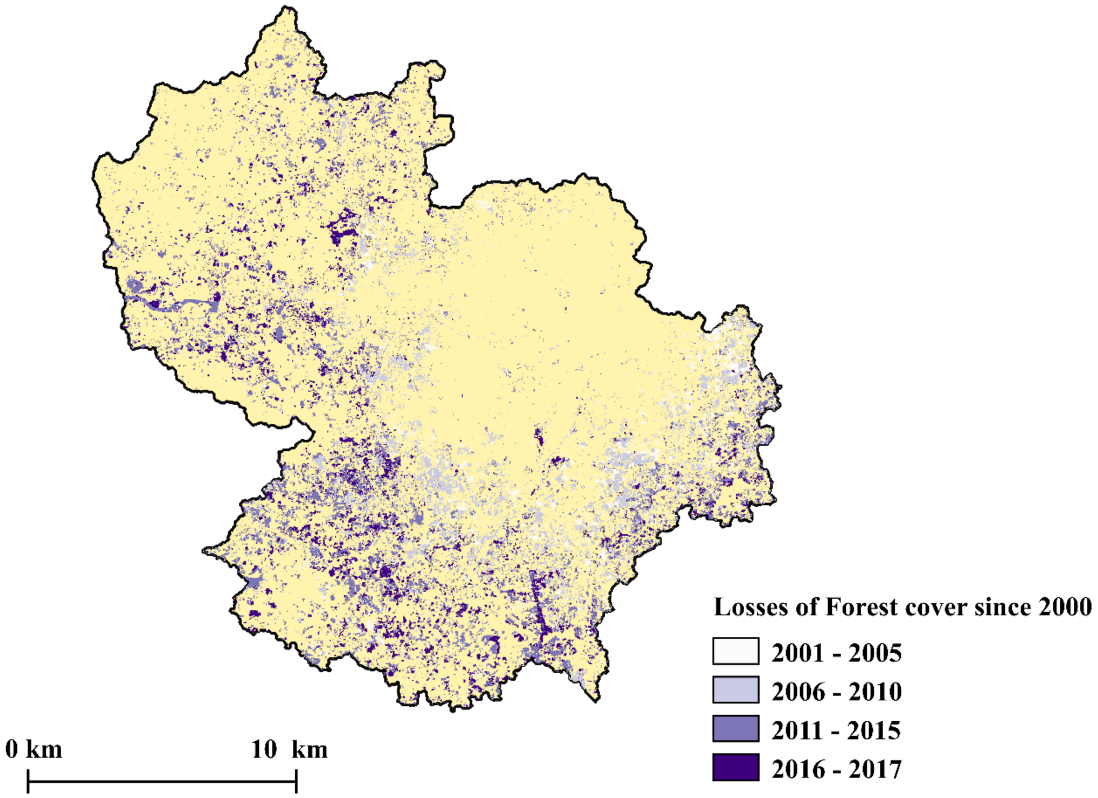


Figure S5. Forest area losses from 2001 to 2017 over the Mefou catchment using the methodology proposed by Hansen et al. (2013).

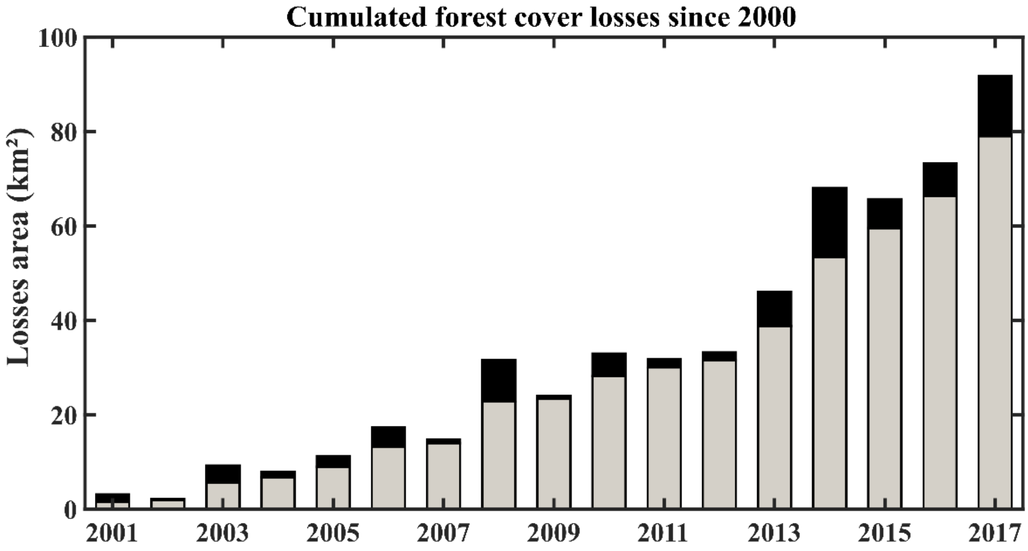
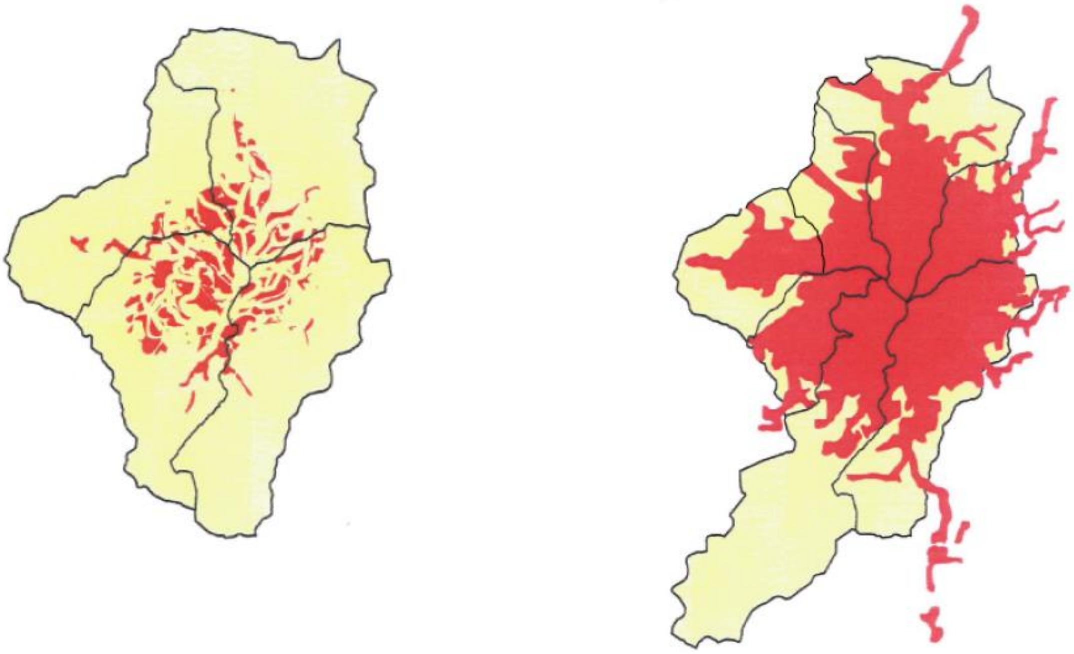


Figure S6. Forest area losses from 2001 to 2017 over the Mefou catchment using the methodology proposed by Hansen et al., (2013).



a. 1980 **b. 2001**

Figure S7. Evolution of Yaoundé urban extension from 1980 to 2001 (CUY, 2008).

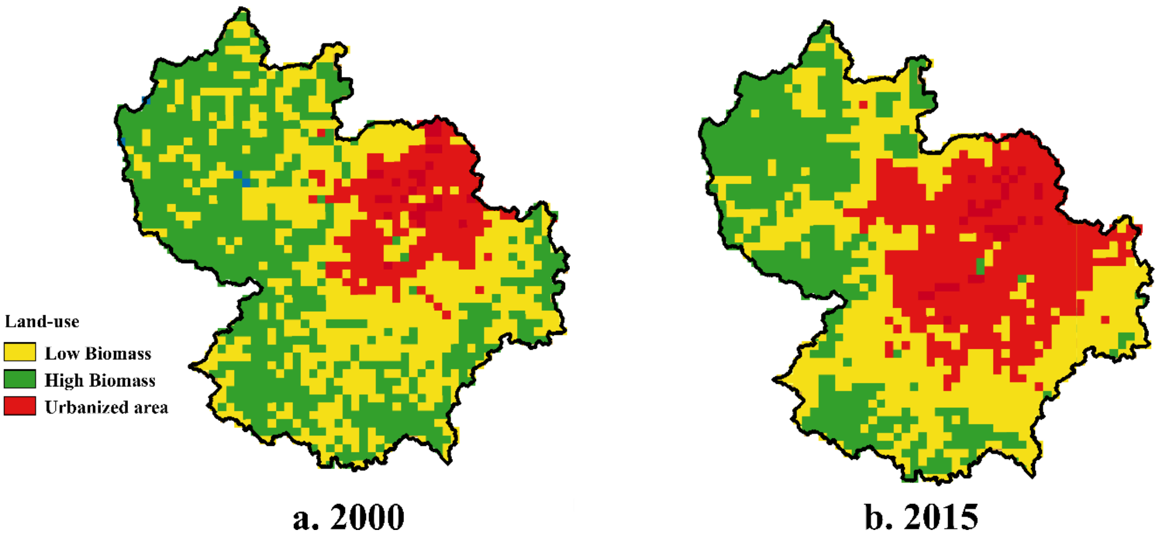


Figure S8. Evolution of the urbanized area, high and low biomass surfaces over Mefou catchment maps from Midekisa et al. (2017).

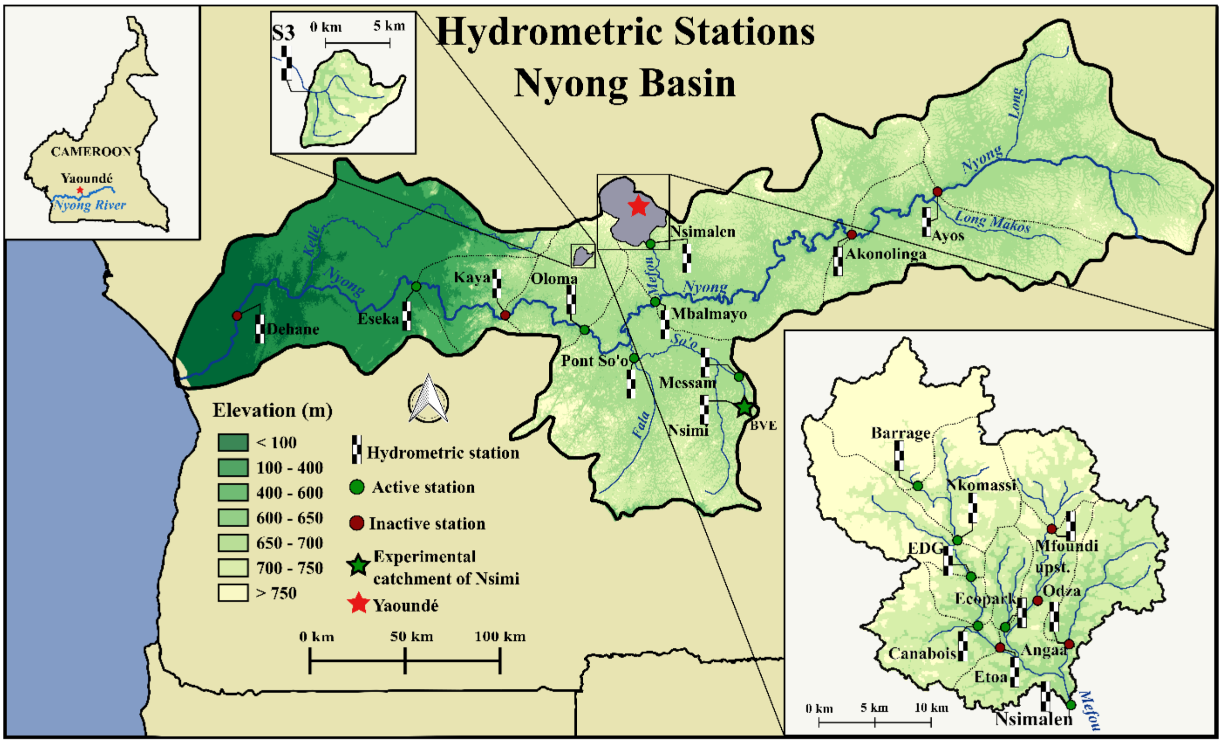


Figure S9. Location of hydrometric stations (active or not) over the Nyong basin.

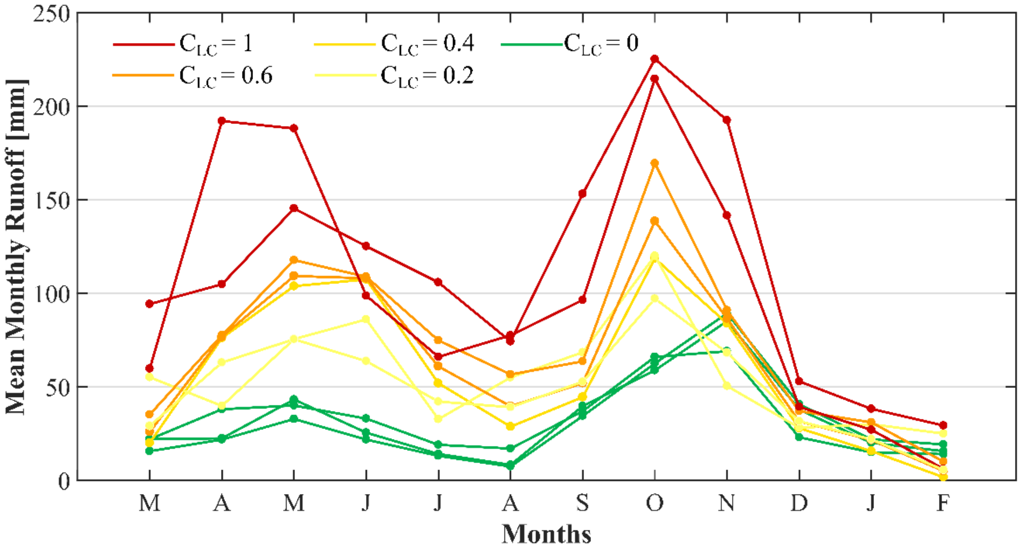


Figure S10. Mean monthly runoff for donor catchments (historical and from the short-term dedicated measurement) used to calibrate the model. Red line : CLC = 1; Orange line : CLC = 0.6Green line : CLC = 0

Tables

Table S1. References of studies on the Mefou catchment used for land-use analysis: For: Forest cover (km^2); Crop : Cropland cover (km^2); Urb : Urbanized area (km^2); Gras : Grassland cover (km^2); Imp : Impervious (km^2).

Reference studies	**Years**	**Location**	**Subject**	**Method**	**Main Results**
Ebodé (2017)	1978, 1995 and 2005	Mefou (305 km^2)	Forest, urban and cropland changes	Analysis of Landsat Images	**Urb**: 45 km^2 (1978 to 152 km^2 (2015) **Crop**: 10 km^2 (1978) to 28 km^2 (2015) **For**: - 30 km^2 from 1978 to 1995 and -130 km^2 from 1978 to 2015
Moffo (2011)	1956 and 2010	Mfoundi upstream (40 km^2)	Impervious changes	Aerial images and shapefile of build-up areas	**Imp**: from 2 km^2 in 1956 to 12 km^2 in 2010
CUY (2008)	1980 and 2000	Urban community of Yaoundé (CUY, 290 km^2)	Extension of the urban area	-	**Urb**: 38 km^2 in 1980 to 159 km^2 in 2001
LMI DYCOFAC	2018	Mefou (802 km^2)	Forest, urban and cropland changes	-	**Urb** : 145 km^2 ; **Crop** : 176 km^2 ; 480 km^2 of dense and degradative vegetation

Table S2. Global product (world or African scale) analyzed over the Mefou catchment to complete past studies (Table S1): For: Forest cover (km²); Crop: Cropland cover (km²); Urb: Urbanized area (km²); Gras: Grassland cover (km²); Imp: Impervious (km²).

Global product	Years	Analyzed area	Resolution	Subject	Method	Main Results
ESA-CCI LC	1992 – 2015	Mefou (421 km²)	300m x300m	Forest, urban and cropland changes	Analysis of Landsat Images	**Urb:** 45 km² (1978) to 152 km² (2015) **Crop**: 10 km² (1978) to 28 km² (2015) **For**: - 30 km² from 1978 to 1995 and -130 km² from 1978 to 2015
ESA-CCI LC for Africa	2016	Mefou (421 km²)	30m x 30m	Forest, urban and cropland	Analysis of Sentinel 2-A images	**Urb**: 113 km²; **Fo**r = 168 km²; **Cro**p = 101 km²; **Gras** = 38 km²
Midekisa et al. (2017)	2000 and 2015	Mefou (421 km²)	30m x 30m	Urban low and high biomass changes	Analysis of Landsat Images	**Urb**: 75 km² (2000) to 158 km² (2015)
Hansen et al. (2013)	2000-2017	Mefou (421 km²)	30m x 30m	Losses in forest cover	Analysis of Landsat images	Losses 95 km² of Forest cover since 2000
OSM (2015)	2015	Yaoundé city (Urban area, 290 km²)	-	Build up area (impervious)	Shapefile from crowdsourced information	Ex: Impervious of 45 % in 2015 for upstream Mfoundi

Table S3. Proportion of urbanized area U (%) for each target catchment for 1930, 1950, 1980, 2000, and 2017.

References used		Franqueville (1979)	Franqueville (1979) and Moffo (2011)	CUY (2008) and Ebodé et al. (2017)	Midekisa et al. (2017)	Midekisa et al. (2017)
Catchment Name	**Station Name**	**1930**	**1950**	**1980**	**2000**	**2017**
T_1	MOPFOU	< 1	< 1	< 1	< 1	< 1
T_2	MEFOU UPST.	< 1	< 1	2 - 5	13	46
T_3	CANA-NKOM	< 1	< 1	< 1	< 1	9
T_4	MEF. DWNST.	< 1	< 1	< 1	< 1	< 1
T_5	MFOUNDI UPST.	< 1	2 - 5	20 - 30	78	90
T_6	BIYEME	< 1	< 1	5 - 20	43	87
T_7	MFOUNDI DWNST.	< 1	< 1	5 - 20	26	63
T_8	ANGAA	< 1	< 1	2 – 5	8	40

Table S4. Annual water balance components for instrumented catchments over the Nyong basin.

Reference	***Name***	***Area [km²]***	***Period***	***P [mm]***	***R [mm]***	***AET [mm]***	ρ	***Land-use***
Lefèvre (1966)	ETOA	235	1965-66	1,420	350	1,070	0.25	Natural
Maréchal et al. (2011)	NSIMI/BVE	< 1	1994-98	1,650	380	1,270	0.25	Natural
Ngoumdoum (2013)	ODZA	6	2011-12	1,840	1640	200	0.88	Very urbanized
Olivry (1979)	AYOS	5,300	26 yrs [1]	1,580	343	1,270	0.22	Natural
	AKONILINGA	8,350	23 yrs [1]	1,545	352	1,192	0.23	Natural
	MBALMAYO	13,555	26 yrs [1]	1,765	315	1,450	0.18	Natural
	OLOMA	15,510	12 yrs[1]	1,563	374	1,189	0.24	Natural
	KAYA	19,985	10 yrs[1]	1,565	389	1,176	0.25	Natural
	ESEKA	21,600	26 yrs [1]	1,581	402	1,179	0.25	Natural
	DEHANE	26,400	25 yrs [1]	1,732	528	1,205	0.30	Natural
Srang (1972)	MFOUNDI UPST.	40	1969-71	1,785	655	1,129	0.37	Intermediate
Ikounga (1978)	S1	2	1974-78	1,609	433	1,176	0.27	Natural
	S2	2	1974-78	1,536	600	937	0.39	Natural
	S3	24	1974-78	1,633	400	1,240	0.24	Natural
Ndam Ngoupayou (2007)	MBALMAYO	13,555	2005-07	1,765	315	1,450	0.18	Natural
Nguemou (2008)	MFOUNDI UPST.	40	2006-07	1,740	1340	400	0.77	Urbanized
SNEC (1969)	ETOA	235	1968-69	1,790	392	1,398	0.22	Natural
SNEC (1969)	MOPFOU	70	1968-69	1,810	456	1,354	0.25	Natural
	MESSAM	206	1998-02	1,780	550	1,230	0.31	Natural
	PONT SO'O	3,070	1998-02	1,750	450	1,330	0.26	Natural

[1] Number of available years before 1979.

Table S5. Monthly runoff for D_{I2} *and* D_{I6}.

Monthly Runoff (mm)	D_{I2}	D_{I6}
September	64	61
October	170	93
November	91	75

Table S6. Results of sensitivity analysis for weight of land-use component in the hydrological index

ω_{LC}	***a***	***b***	***I =1*** ***a + b***	***I=0.5***	r^2
3	0.827	0.096	0.923	0.51	0.83
5	0.766	0.130	0.896	0.51	0.95
7	**0.708**	**0.158**	**0.866**	**0.51**	**0.97**
10	0.656	0.186	0.842	0.51	0.98

Table S7. Sensitivity analysis of number of donors *N* on the model parameters *a* and *b*. Indices *1* and 2 refer respectively to the calibration and the validation period, *1 + 2* refers to the whole period. The criteria functions are given in Sect. 2.2.

***N* Donors**	***a***	***b***	***RMSE₁***	***RMSE₂***	***RMSE₁₊₂***	***r²₁***	***r²₂***	***r²₁₊₂***	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_{1+2}$
6	0.67 ± 0.05	0.13 ± 0.02	76 ± 4	123 ± 2	102 ± 3	0.76± 0.03	0.60± 0.03	0.66± 0.03	0.12	0.19	0.16
8	**0.70 ± 0.02**	**0.12 ± 0.01**	**73 ± 2**	**124 ± 3**	**101** ± 3	**0.78**± 0.01	**0.60**	**0.66**	**0.12**	**0.19**	**0.15**
9	0.69± 0.02	0.13 ± 0.01	73 ± 1	124 ± 2	101 ± 2	0.78	0.60	0.66	0.12	0.19	0.15
10 (all)	0.70	0.13	73	124	101	0.78	0.60	0.66	0.12	0.19	0.15

Table S8. Studies of land-use changes impacts on annual runoff in tropical context.

Reference	Data / Model used	Location/ Study Size	Precipitation P/ Annual Runoff R/ Annual runoff coeff. ρ/	Main land-use	Land-use changes	Hydrology Impact
Descroix et al. (2009)	SPOT image + Gauge data – Review	West Africa / Sudanian and Sahelian region	High varieties of annual water balance components	Bush convert in cropland	10 % of the Nigerian Sahel was covered by cropland in 1950s and close to 80 % in 2010	In the Sudanian areas, stream flows have been reduced, sometimes as much as twice the rainfall reduction rate. In the Sahelian regions, runoff coefficients have increased to such a degree that discharges are increasing, in spite of the reduced rainfall.
Beck et al. (2013)	Landsate data/HBV-LIGHT	Puerto-Rico/ 12 catchments between of 24 - 177 km²	P = 1720 to 3422 mm	Pasture, cropland and Forest	Forest regeneration	LULC and runoff at large scale no (strongly) related
Giertz et al. (2006)	Gauged data	Benin/ 16.5km²	P = 1140-1215 mm R = 140-185 mm ρ = 0.12-0.15	Woodlands and Savannah	no change	ρ between 0.12 – 0.15

Table S8. Continuation of the previous Table.

Reference	Data / Model used	Location/ Study Size	Precipitation P/ Annual Runoff R/ Annual runoff coeff. ρ/	Main land-use	Land-use changes	Hydrology Impact
Yira et al. (2016)	SRTM90m, LANDSAT, gauged data/ WaSim	Burkina Faso / Dano catch. 195 km²	**2013** : P = 966 mm R = 145 mm ρ = 0.15	**1990** Tree and Savannah (87 %); Cropland (12 %); Urban (0.1 %) **2013** Tree and Savannah (59 %); Cropland (38 %); Urban (3.6 %)	Decrease of savannah at an annual rate of 2 % since 1990 (convert in cropland and in lesser extent in urban area)	Up to 5% of increase in R due to conversion between 1990 and 2014
Gessess et al. (2015)	Gauged data, LANDSAT / SWAT	Ethiopia / Modjo catch.1478 km²	**2017** P = about 900 mm R = 172-304 mm ρ = 0.20-0.33	**1973** Cropland (55 %) Grassland (22 %) Shrubland (14.4 %) Urban (3.7 %) **2007** Cropland (75 %) Grassland (5.5 %) Shrubland (8.5 %) Urban (5.0 %)	Decrease of grassland and shrub land convert in cropland and urban area in a lesser extent	Increase of R from 14.3 % to 36.6 % depending of scenarios. R increases from 125-285 mm to 172-305 mm.

Table S9. Studies of urbanization impacts on annual runoff in tropical context.

Reference	Data / Model used	Location/ Study Size	Precipitation P Annual Runoff R Annual runoff coeff. ρ	Main land-use	Land-use changes	Hydrology Impact
Jennings and Jarnagin (2002)		Accotink Creek, Virginia, USA/ 61 km²	-	-	Urban area increased from 13 % to 21 %	Increase of 50 to 100% on streamflow response to rainfall
Sillanpää and Koivusalo (2015)	Gauged data	Finland, Saunalahdenranta catc./ 13.2 ha	P = 650 - 700 mm	Urban area	Urban area increased from 1.5 to 37 %	Increase of 45% on storm runoff
Braud et al. (2013)	Gauged data	France, Yzeron/ 150 km²	P = 750 mm	Agriculture (1970) to Urban (2008)	artificialized soil : 1970 = 22% 2008 = 36%	Significate increase of quick flow and significate decrease of inter and base flow.
Beighley et al., (2003)	Gauged data / HEC-HMS	Atascadera Creek , California, USA/ 50 km²	Average for 1940-2000 : P = 610 mm R = 100 mm ρ = 16.5 %	Shrubs (51% in 2003) to Urban	Urban area changed : 1929 = 8 % 1998 = 38 % 2050 = 52 % (estimation)	R_1929 = 70 mm R_1998 = 150 mm R_2050 = 220 mm
White and Greer (2006)	Gauged data	San Diego county, California, USA/ Los Penasquitos Creek, 158 km²	P = 250 mm	Urban area = 37 % Agriculture = 5% Vegetation = 55%	Urban area changed 1965 = 9 % 2000 = 37 %	Increase of 4% per year of R between 1973 and 2000
Dietz and Clausen (2008)	Gauged data	Waterford, USA/ Jordan Cove, 2 ha	-	-	Impervious fom 1% (1994) to 32% (2006)	R increased from 1 mm to 500 mm
Barron et al. (2013)	Gauged data /MODHMS	Swan Coast Plain, Australia / Southern River catch. (150 km²)	P = 786 mm R = 80 mm ρ = 11%	-	High urbanization	ρ increased from 0.01 to more than 0.40 AET reduced from 63-68 % to less than 2 9% of rainfall

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