Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-623, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 25 November 2016

Hydrology and Earth System Sciences
Open Access
Discussions

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

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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.

In this paper, a modeling approach is proposed to 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, in the Gourma region in Mali, which underwent a significant increase in surface runoff during the last 60 years. Two periods are simulated, the "past" case (1960-1975) preceding the Sahelian drought and the "present" case (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 giving place to impervious soils. These changes were implemented independently and in combination in the KINEROS-2 model. The simulations results show a significant increase of annual discharge between the "past" and the "present" case (p value < 0.001) despite a slight overestimation of the past discharge. Mean annual discharges are estimated at 0.51×106 m^3 and 3.29×106 m^3 for past and present respectively.

Modification of soil properties and vegetation cover (grassland and tiger bush thickets) are found to be the main factors explaining this increase, with the drainage network development contributing to a lesser extent. These synergistic processes explain the Sahelian paradox in the absence of land use change and could play a role in other Sahelian watersheds where runoff increase has been also observed.

Keywords: Sahelian paradox, Annual discharge, KINEROS-2, Evolution

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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 had dramatic impact on people and ecosystems (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 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) fort 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). 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 the reduction in vegetation cover and top soil crusting 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 enhance 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 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). Attribution studies inferring the impact of the different factors detailed above on surface runoff are therefore lacking.

The objective of this study is: 1) to analyze the soil, land cover and hydrological changes that occurred over the Agoufou watershed since the 50ies and 2) to quantify and rank the impact of these changes 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 River 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).

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 Upper Precambrian schists and sandstones partially covered by staggered ferricrete surfaces (Grimaud et al., 2014), silt depositions and sand dunes. The site is extensively described in Gal et al.

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(2016). The northern part of the watershed (Fig. 1) consists of shallow soils lying on sandstone, schist or iron pans. Some of these soils are fine textured soils (silt flats) and most of them 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 0.22 %.

The vegetation is typical Sahelian vegetation with herbaceous composed of annual plants, plus scattered bushes and low trees (Boudet, 1972; Hiernaux et al., 2009a, 2009b). The herbaceous layer is discontinuous on shallow soils and leaves large bare areas prone to runoff, whereas it is nearly continuous on deep sandy soils. Tree crowns usually occupy between 0 and 5 % (Hiernaux et al., 2009b). Trees tend to concentrate along reaches and gullies, around ponds, and in inter-dune depressions. On shallow soils, linear thickets sometimes grow perpendicular to the slope. This ecosystem is called “tiger bush” or banded vegetation (Hiernaux and Gérard, 1999; Leprun, 1992). These thickets strongly limit runoff 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.

2.2 KINEROS-2 description

The KINematic EROSion model (KINEROS-2) 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 arid and semi-arid 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 GIS-based interface (Miller et al., 2007). From the topography, AGWA discretizes the watershed into CSA

(Contributing Source Area), which are considered as homogenous. Hydrological parameters for each CSA are derived from soil surface characteristics maps based on soil texture (FAO classes) and vegetation properties.

2.3 Input data

K2 needs four input dataset 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.

2.3.1 Digital elevation model (DEM)

Two 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 DEM 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 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 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 he 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 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 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 are used as input to the grass layer sub-model (see Sect. 3.2.3).

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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 outflow are available for 17 years between 1965 and 2015, depending on the availability of the satellite data.

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), erosion surface units (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) and studies carried out in the Sahel by Casenave and Valentin (1989), Valentin et Janeau (1988), Kergoat et al. (in prep) and Diallo and Gjessing (1999).

For the past period, photo interpretation of stereo-pairs is used so that 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 minimal.

3.2 Model setup and watershed representation

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. For each DP event, ten 5M events of the LUT are retained to perform ensemble 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 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. The 5-minutes rates are rescaled so that the daily total amounts are the exactlysame.

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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. 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. 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

The number of CSAs determines the level of geometric complexity in the discretization of the watershed (Thieken et al., 1999) with more CSAs producing more elements and a more developed drainage network. Ideally, the complexity of the simulated watershed is consistent with the watershed 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 size depends on the case study, but a value smaller than 2.5 % of the total watershed area, is commonly selected. For this study, the number of CSAs was selected to correspond to the drainage network found in both 1956 and 2011 and to reach a good compromise between simulation time, watershed complexity and homogeneity of CSAs (Fig. 2): 174 CSAs with a mean area of 1.4 km² have been retained, which corresponds to 1 % of the total watershed area.

The same number of CSAs retained for the present and the past cases, assuming that the broad features of the DEM did not change between the two periods (slopes of cascading planes). However, the drainage network has changed between these periods. To account for this, the DEM derived network 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 versus DEM-derived network length for each sub-watershed.

3.2.3 Derivation of soil characteristics

FAO codes used by AGWA are assigned to all landscape units defined in Table 2 to match as closely as possible the soil texture and depth, known from field survey and previous knowledge of the study region. Table 3 summarizes the hydrological parameters assigned to each landscape unit by AGWA 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, grassland, sparse trees, tiger bush tickets, woody plant and no vegetation, 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 is particularly sensitive to vegetation cover (Table 4). The saturated hydraulic conductivity 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 (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). 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). 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 MAN and CC were attributed based on ecosystem survey, GeoEye-1 imagery and K2 literature.

The saturated hydraulic conductivity (KS) value based on the soil texture is 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 Model Calibration and Validation

Model calibration is performed by tuning channel properties (MAN and KS) since channels parameters are less documented than plane parameters. Calibration is carried out for the period 2011-2015 (n=5) which benefits from numerous and accurate observations.

A total of thirty sets of KS and MAN parameters values are used to sample the 10-50 $mm.hr^{-1}$ and 0.01-0.05 domain, corresponding to literature values for semi-arid zones (Chow, 1959; Estèves, 1995; Peugeot et al., 2007). Each set of parameters is used to run the ten simulations corresponding to a disaggregated precipitation ensemble (see Sect. 3.2.1). Parameters leading to the minimum bias (Eq. (3)) on the annual discharge are retained. These optimum parameters are then used to run K2 for 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).

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

Where *sim* is the simulated annual discharge and *obs* is the observed annual discharge.

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3.4 Reference and attribution simulations of the Agoufou watershed

Two references simulation cases are designed together with a suite of academic simulations to quantify and rank the effects of the 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). 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 environmental changes, identified by the comparison of the Agoufou watershed between 1956 and 2011 (see Sect. 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 factors, considered in the different simulations is expressed as a fraction of the difference between present and past mean annual discharge (Eq. (3)), where 100 % corresponds to the past discharge and 0 % to the present.

$$Ex = \frac{(AQpr - AQx)*100}{(AQpr - AQpa)} \qquad (4)$$

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

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. 3, 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 5 and Fig. 4). 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 km² in 1956 to 12 km² 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 km² in 2011 against 2.5km² 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 E1 sand sheets to O2 outcrops. Overall, the surface of the outcrop classes has increased from 18 km² in 1956 to 27 km² in 2011.

Erosion surface (E): Although the overall proportion of erosion surface unit (E) on the watershed has not really changed between 1956 and 2011 (24% and 26% respectively), this unit underwent the greatest changes in terms of hydrological properties. Indeed, all tiger bush units (E3) have completely disappeared and an important erosion of the underlying soil has occurred. Impervious bare soils have replaced most of these areas, sometime leaving some rare trees or bushes, witnesses of the old tiger bush (E4). In addition, the silt layer (E2) has increased from 7 km² to 11 km², mainly in areas where the drainage network highly developed, reflecting the transition from sheet runoff to concentrated runoff. 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 calibration period is obtained with a channel MAN of 0.03 and a channel KS of 30 mm.hr^{-1} (Fig. 5). The corresponding bias is 2.7 % of the averaged discharge and the RMSE is equal to 6.4×10^5 m^3 (n=5). As expected, several combinations of MAN and KS give close results, higher MAN compensating lower KS. The optimized values of MAN and KS correspond to rather impervious channels, which infiltrate much less than what is found in the literature for Sahelian watersheds, which reports a MAN close to 0.03, but a KS commonly 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.

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 (n=6) showing that the model performs reasonably well. For both the 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. 6). 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 3.85×10^6 m^3 (n=6) and 3.72×10^6 m^3 (n=5) for the validation and calibration period respectively against 3.47×10^6 m^3 (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 (n=11)

4.3 Long term evolution and attribution of changes

4.3.1 Long term evolution

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. 7), namely 11 years for the present and four years for the past. Both simulated and observed discharges showed an important increase over time, with a mean simulated discharge of 0.5×10^6 m^3 (n=15) and 3.29×10^6 m^3 (n=15) for the past and present periods respectively to be compared with 0.02×10^6 m^3 (n=4) and $3.43.10^6$ m^3 (n=11) for the observations. For the past period, simulations overestimate the annual discharge for all the four years with observations. The simulated runoff coefficient over the whole watershed (ratio between annual discharge and the precipitation over the total watershed area) is estimated at 0.55 % (n=15) and 3.87 % (n=15) for the past and the present periods respectively against 0.02 % (n=4) and 4.0 % (n=11) for the observations.

Despite the past simulations being overestimated and modeled variability being slightly larger than observed variability, both simulations and observations 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).

4.3.2 Attribution of changes

Results from the K2 simulations outlined in 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.

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 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-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 while the contribution of the network development over the Z2, Z3 and Z4 is equal to 3.6×10^5 m^3, 1.5×10^4 m^3 and

1.2×10^4 m^3 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 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 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 (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". Vegetation efficiently slows surface runoff and increases infiltration capacity. As a result, simulation "V" produces a discharge of 2.1×10^6 m^3 and herbaceous vegetation changes explain **42 %** of the difference in surface runoff between past and present.

Modification of the soil properties (S): This simulation tests the impact of soil modifications on annual discharge independently of the herbaceous cover fraction, which is also an academic simulation. The fraction of all landscape units in each CSA is defined by the past land cover map (Fig. 3a). The increase in erosion surfaces and outcrops over time, results in a very strong increase in surface 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" 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. The result is an increase of 8.5×10^5 m^3 of the discharge, at odds with its observed 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 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 explain the changes in watershed 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.

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Manuscript under review for journal Hydrol. Earth Syst. Sci.
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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 change". Overall, despite the uncertainties related to the photo-interpretation and mapping of landscape units, the 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. (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). 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.

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 are present nowadays in the Agoufou watershed, as a result of

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-623, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 25 November 2016

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).

5.2 A significant discharge increase despite the simulation limitation

If simulations and observations are in good agreement for the present period, simulated discharge for the past period is overestimated ($0.51.10^6$ m^3 and $0.02.10^6$ m^3 for simulation and observation respectively). Different reasons could explain this: first, the error bars in Fig. 7, 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 calibrated and validated with all available observation data over the 2000-2015 period, when data are the most accurate and numerous. 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, 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) 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, see **Erreur ! Source du renvoi introuvable.**). 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 largely explain the 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 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 decrease in vegetation cover changed the topsoil hydraulic properties, which enhanced Hortonian runoff. 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).

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 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 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 show that the impact of crusted sandy dune on the surface runoff is 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 considered as part of vegetation and soil changes ("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 show 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"), surface runoff is shown to decrease rather than increase 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, 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 understand 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 giving 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. Evolution of soil properties and vegetation (grassland and tiger bush thickets) largely explained the increase of surface runoff observed between the past (1960-1975) and the present period (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. These synergistic processes explain the Sahelian paradox in the absence of land use changes.

The results reported here 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.

Acknowledgement

We thank Nogmana Soumaguel, Ali Maïga, Hamma Maïga and Mamadou Diawara for collecting data and Eric Mougin for managing the Gourma site and providing the STEP model. We also acknowledge Shea Burns and Carl Unkrich for their feedbacks on AGWA and K2. This research was based on data from the AMMA-CATCH observatory and partially funded by the ESCAPE ANR-project (ANR-10-CEPL-005).

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Datasets	*Type*	*Acquisition date*	*Sources*
DEM	SRTM (30 m)	23 September 2014	NASA
Satellite images and aerial photographs	SPOT (5m)	19 March 2004	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

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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 200cm deep topping bedrock. Hydrological characteristics are close to those of the dune systems (S2) as the soil retention capacity is seldom exceeded.
	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.
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 E1.
	O2: Hard pan outcrop	Hard pan outcrop largely devoid of vegetation. Infiltration is very low. See also E1.
Erosion surfaces (E)	E1: Rocky erosion surfaces	These 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 **(E1v).**
	E2: Silt layer	These 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.
	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 thicket areas have high infiltration capacity. When not degraded, tiger bush systems produce little runoff (downstream) overall.

	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.
Flooded zones (F)	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).

Infiltration	Landscape units	KS mm/hr	G mm	DIST -	POR cm^3/cm^3	FR (S-S-C) %	THICK mm	SMAX %
-	O1-O2-E1-S1c	0	0	0	0	0-0-0	n/a	0
	E2	5.82	224.2	0.38	0.414	5-17-28	n/a	86
	E4-F1	11.82	108	0.25	0.463	36-41-22	n/a	94
	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: 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 (-)	CC (%)	KSnew (mm/hr)
GT	Grassland + Trees	S1-S2-S3-S4	0.008*CCd	CCd	$KS.e^{(0.0105*CCd)}$
G	Grassland	E1v	0.008*CCs	CCs	$KS.e^{(0.0105*CCs)}$
T	Sparse trees	E4	0.05	3	$KS.e^{0.0315}$
TB	Tiger bush thickets	E3	0.6	30	$KS.e^{0.315}$
W	Woody plant	F1	0.05	20	$KS.e^{0.21}$
R	No vegetation	O1-O2-E1-E2-S1c	0.001	0	0

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

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Simulations	Crusted dune	Drainage Network	Vegetation	Soil	Precipitations
Present	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
Past	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 drainage network, the evolution of vegetation cover and soils and the modification of the daily precipitation regime.

Zones	Area (km²)	Total network length (km)		Increase factor
		1956	2011	
Z1	20.72	6.1	17.3	2.85
Z2	30.17	10.1	23.4	1.93
Z3	12.48	6.4	11.1	1.75
Z4	3.5	0.2	3.4	14.01

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

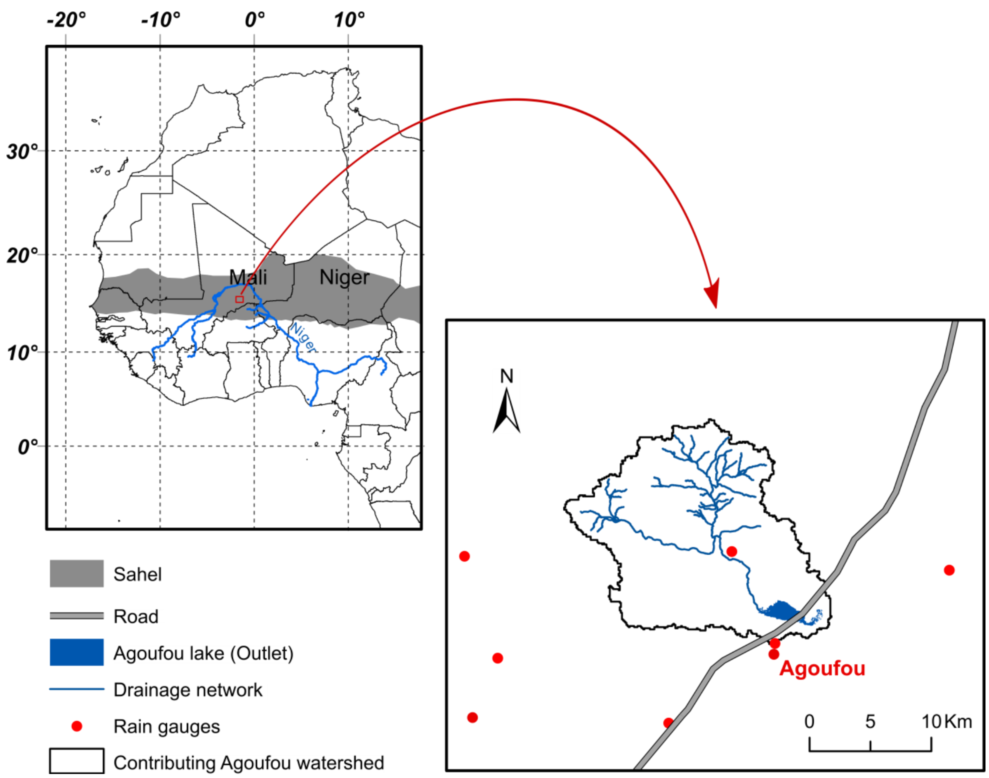

Fig. 1: The Agoufou watershed (245 km²) located in western Sahel (Mali) with drainage network and available rain gauges (map source: http://www.diva-gis.org/gdata).

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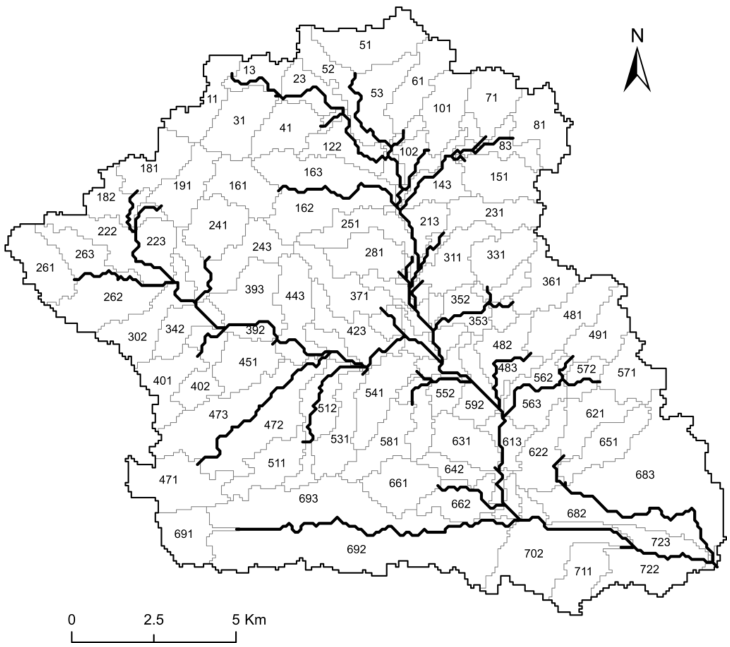

Fig. 2: CSAs for the Agoufou watershed with the DEM-derived drainage network.

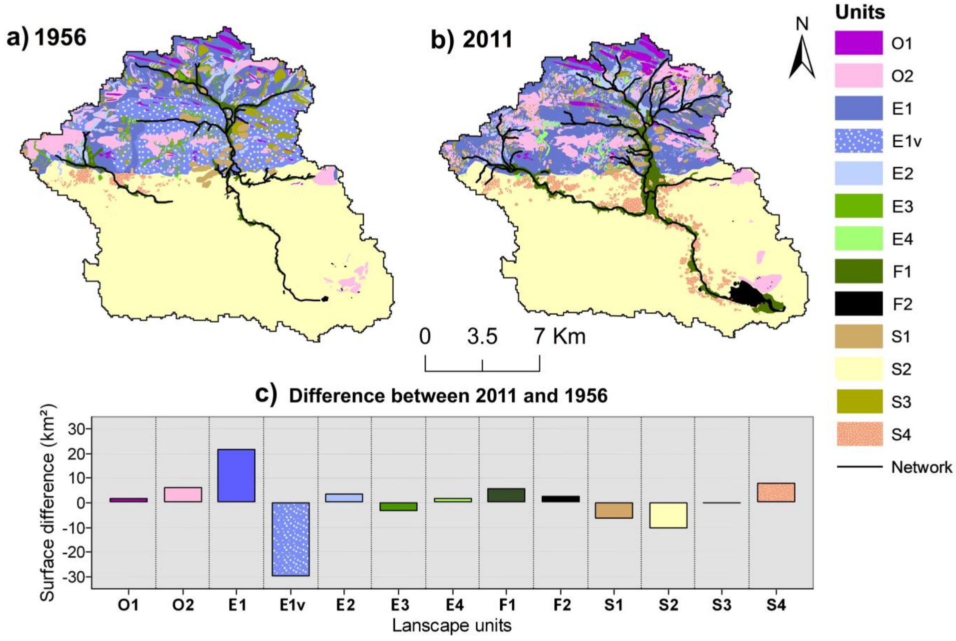

Fig. 3: Land cover maps of the Agoufou watershed for (a) 1956, (b) 2011 and (c) gives the surface difference (in km²) for each landscape unit, between 2011 and 1956.

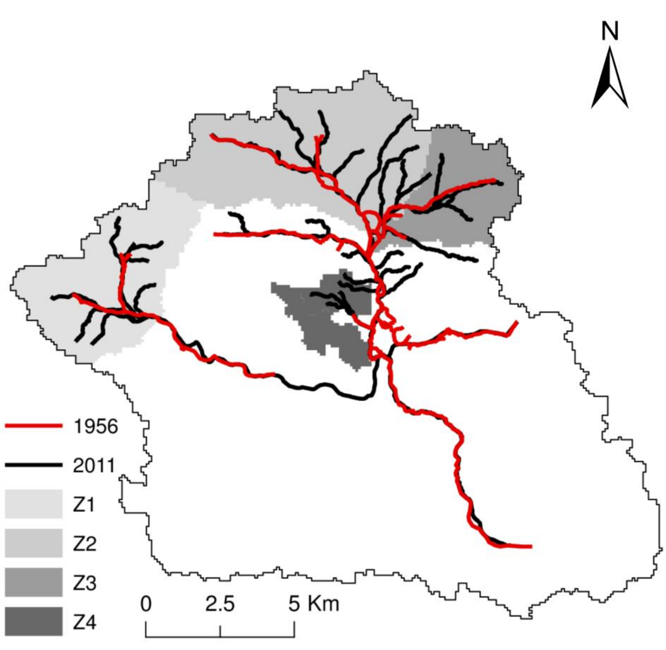

Fig. 4: Identification of the four sub-basins (grey shades) which display the largest changes between the drainage network in 1956 (red line) and in 2011 (black line).

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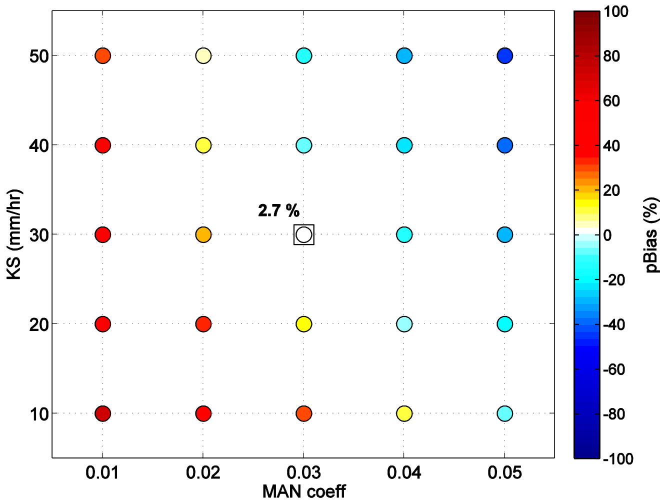

Fig. 5: Percent bias on annual discharges over 2011-2015 for 25 sets of channels KS and MAN parameters. The minimum value is indicated by the square box.

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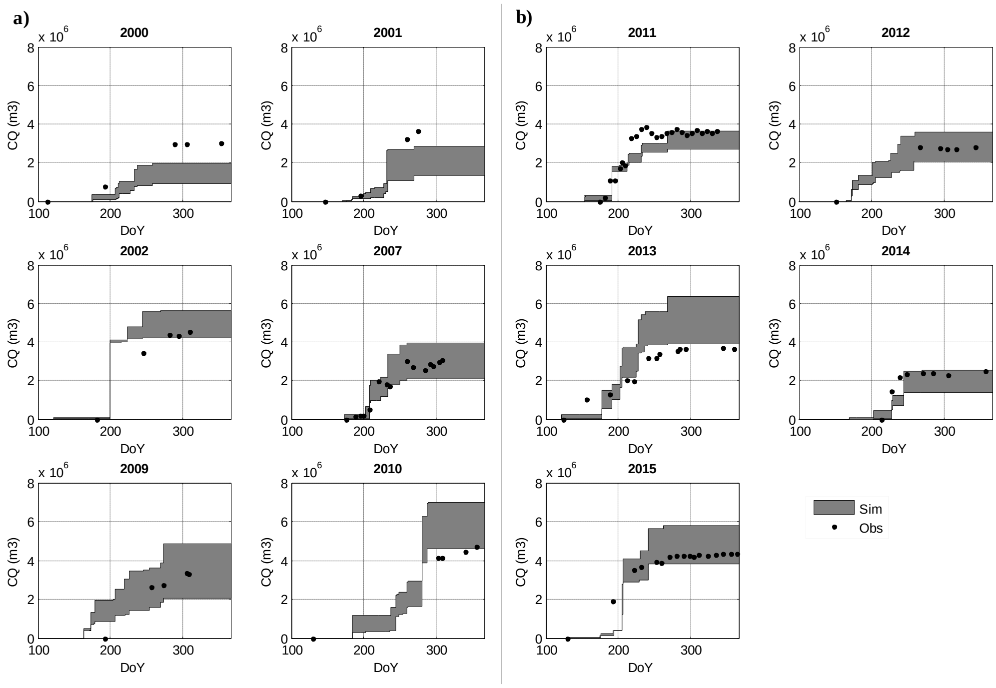

Fig. 6: Cumulative discharge (CQ) for years with observation data over 2000-2015. For each year, black dots are for the observations and the gray-shaded envelop represents the maximum and minimum of the ten members of the ensemble simulations. (a) is for the validation period and (b) is for the calibration period.

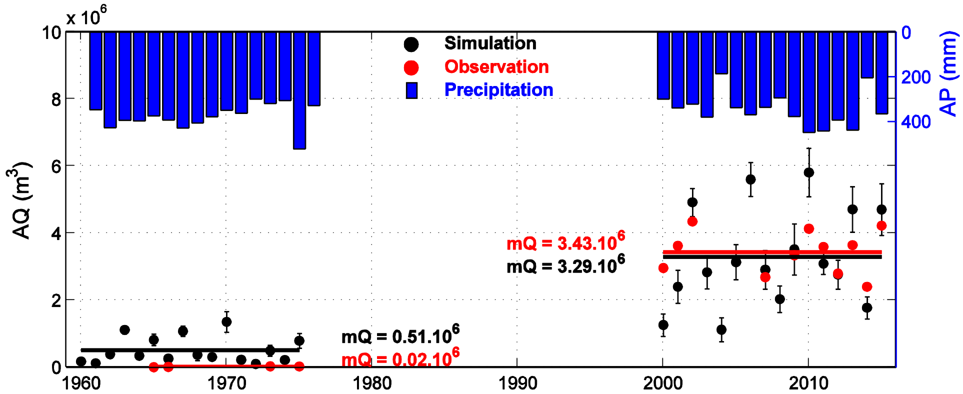

Fig. 7: Evolution of annual discharge (AQ in m3) between 1960 and 2015: simulations with standard deviation of the ten members (black dots with error bar) and observations (red dots) together with annual precipitation (AP in mm, blue bars).

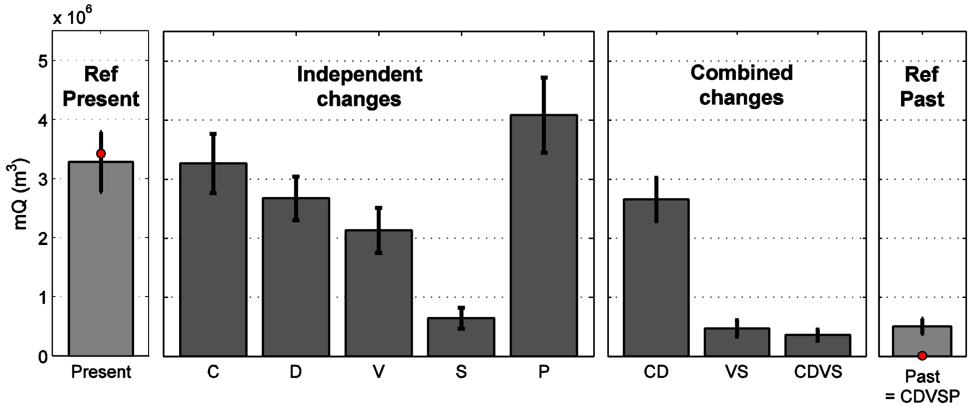

Fig. 8: Mean discharge (mQ) for present and past reference cases and for the attribution simulations described in Table 5, with either independent or combined factors. For the references cases, observation data are added (red points). Errors bars indicate the standard deviation of the ten member and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