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Research papers

Changes in lakes water volume and runoff over ungauged Sahelian watersheds

L. Gal [a,*], M. Grippa [a], P. Hiernaux [a], C. Peugeot [b], E. Mougin [a], L. Kergoat [a]

[a] Géosciences Environnement Toulouse (GET), UMR 5563, Université Toulouse 3, CNRS, IRD, 14 avenue Edouard Belin, OMP, 31400 Toulouse cedex 9, France
[b] HydroSciences Montpellier (HSM), UMR 5569, IRD, Université Montpellier 2, CNRS, 300 avenue du Professeur Emile Jeanbrau, 34095 Montpellier cedex 5, France

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ABSTRACT

A large part of the Sahel consists of endorheic hydrological systems, where reservoirs and lakes capture surface runoff during the rainy season, making water available during the dry season. Monitoring and understanding the dynamics of these lakes and their relationships to the ecohydrological evolution of the region is important to assess past, present and future changes of water resources in the Sahel.

Yet, most of Sahelian watersheds are still ungauged or poorly gauged, which hinders the assessment of the water flows feeding the lakes and the overall runoff over their watershed.

In this paper, a methodology is developed to estimate water inflow to lakes for ungauged watersheds. It is tested for the Agoufou lake in the Gourma region in Mali, for which *in situ* water height measurements and surface areas estimations by remote sensing are simultaneously available. A Height-Volume-Area (HVA) model is developed to relate water volume to water height and lake surface area. This model is combined to daily evaporation and precipitation to estimate water inflow to the lake, which approximates runoff over the whole watershed. The ratio between annual water inflow and precipitation increases over the last sixty years as a result of a significant increase in runoff coefficient over the Agoufou watershed.

The method is then extended to derive water inflow to three other Sahelian lakes in Mauritania and Niger. No *in situ* measurements are available and lake surface areas estimation by remote sensing is the only source of information. Dry season surface area changes and estimated evaporation are used to select a suited VA relationship for each case.

It is found that the ratio between annual water inflow and precipitation has also increased in the last 60 years over these watersheds, although trends at the Mauritanian site are not statistically significant.

The remote sensing approach developed in this study can be easily applied to recent sensors such as Sentinel-2 or Landsat-8, to quantify the evolution of hydrological systems in ungauged Sahelian regions.

1. Introduction

During the second half of the 20th century, the Sahel has been characterized by a severe rainfall deficit, with extreme droughts in 1972–73 and again in 1983–84, which have strongly impacted ecosystems, water availability, fodder resources, and populations living in these areas. However, an increase of surface runoff has been observed during the same period: higher discharge of Sahelian rivers, generating local floods, and a general increase in lake's surface in areas of central and northern Sahel (Albergel, 1987; Descroix et al., 2012; Gardelle et al., 2010; Mahé et al., 2010, 2003; Sighomnou et al., 2013). This behavior, less rain but more surface runoff is generally referred to as the "Sahelian paradox" (see Descroix et al. (2009) for extensive discussion).

Various hypotheses have been put forward to explain this paradoxical situation. The leading role of an increase in cropped areas, often cited for cultivated Sahel (Favreau et al., 2009; Leblanc et al., 2008; Mahé and Paturel, 2009), does not hold for pastoral areas in central and northern Sahel (Gardelle et al., 2010). Processes such as degradation of vegetation subsequent to the most severe drought events (Dardel et al., 2014; Trichon et al., 2012), soils erosion, runoff concentration affecting shallow soils, which generate most of the water ending up in lakes, and/or an intensification of the rainfall regime (in fact an increase in the occurrence of the largest daily rainfall amounts; Nicholson, 2013; Panthou et al., 2014), seem to play an important role, but this paradox is not fully understood yet.

* Corresponding author.
E-mail address: gal.laetitia@gmail.com (L. Gal).

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Modeling can help identify the phenomena responsible for this increase in surface water but hydrological models require calibration using data which are often unavailable for Sahelian watersheds. Indeed, watersheds in many parts of the world and particularly in endorheic semi-arid regions, are poorly gauged and, in some cases, data availability is declining (Sivapalan et al., 2003). Runoff estimation in ungauged watersheds is one of the most important tasks of hydrologists according to Seibert and Beven (2009).

In the absence of *in situ* data, reservoirs and lakes can be used as runoff gauges (see Fowe et al. (2015) for a recent example in Burkina Faso). This requires water storage estimates that can be obtained using what Rodrigues et al. (2012) called "indirect methods". Such methods consist in combining water area derived by remote sensing with Area-Volume relationships (Liebe et al., 2005, 2009). These relationships can be established using for example information from remote sensing and local topography (Magome et al., 2003; Soti et al., 2010), information from reservoir managers (Cecchi et al., 2009) or more simple data like heights of dams and maximum size of open water (Rodrigues et al., 2012). An alternative is to look for Area-Volume relationships that are valid at the regional scale, assuming topography (for lakes and reservoirs) and design of dams (for reservoirs) share some degree of similarity at this scale. As far as Africa is concerned, Meigh (1995) and Sawunyama et al. (2006) developed a simple method to estimate reservoirs storage using surface areas. They assessed the impact of small farm reservoirs on urban water supplies in Botswana as well as the storage capacities of small reservoirs by using remotely sensed water surfaces in Mzingwane (Zimbabwe) and a relationship between surface areas and storage capacity given by a HVA (Height-Volume-Area) model. Similar approaches were successfully developed for the Upper East Region of Ghana by Liebe et al. (2005) and Annor et al. (2009). In Senegal, Soti et al. (2010) assessed the spatio-temporal dynamics of ponds (the Niaka and Furdu ponds) using ponds shapes derived by *in-situ* bathymetry and remote sensing. Apart from Soti's work, few studies have been carried out in the Sahel, and therefore there is limited knowledge of the applicability of indirect gauging methods in this region, which combines with an extremely low number of direct gauging sites. As a result, lake water inflow and runoff coefficients in endorheic Sahel are extremely poorly documented, and their evolution in the long term still is a major obstacle to a proper understanding of the processes behind the Sahelian paradox.

The objectives of our study are: (1) to develop and test a method for estimating the water inflow to the Agoufou lake (central Sahel in Mali) to be used as a proxy for runoff over its watershed, (2) to propose a general method to estimate water inflow to lakes in other Sahelian regions based on satellite data acquired during the dry season, which are used to select the most appropriate Area-Volume (AV) relationship and (3) to quantify the evolution of water inflow and runoff over the last sixty years in different Sahelian regions.

2. Materials

2.1. Study sites

The main site used for this study is the Agoufou watershed (lat 15.37°; lon −1.47°). It is located in the Gourma region, in northern Mali, covers an area of 183.5 km^2 (Fig. 1) and is representative of endorheic areas in pastoral Sahel (Gardelle et al., 2010).

The climate is warm 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 a varying number (12–35) of tropical convective events brought by the West-African monsoon (Frappart et al., 2009; Vischel and Lebel, 2007). It shows a spatial and interannual variability, which superimposes to a multi-decadal variability. As elsewhere in the Sahel, the long term evolution of precipitation (Fig. 2) is characterized by a wet period in the 1950–60s, followed by a long dry period, with two extreme drought events in 1972–73 and in 1983–84. The last 15 years have shown a partial recovery in rainfall, with extreme events seemingly occurring more often (Frappart et al., 2009; Panthou et al., 2012). Important drought are still occurring, such as in 2004, 2008 and 2014 for the Gourma region.

The topographic watershed of the Agoufou lake lies on Upper Precambrian schists and sandstones. These schists and sandstones were folded and densely faulted, and then leveled by a long history of erosion that, during Cenozoic, established three embedded ferricrete surfaces whose hard pan remnants structure the upper watershed (Grimaud et al., 2014).

The upstream portion of the Agoufou watershed (Fig. 1) consists of shallow soils on bedrock (sandstone, schist or iron pans) interspersed with rocky outcrops and iron pans. Most of these shallow soils are fine textured soils, prone to crusting. These shallow soils,

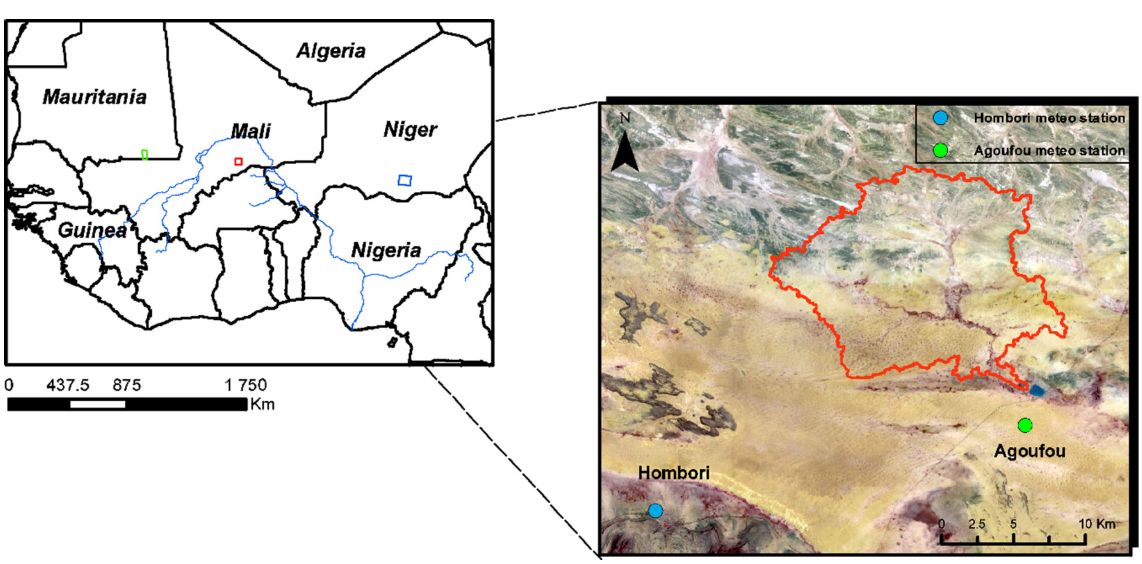

Fig. 1. Study sites in West Africa: Mauritania (Tourh & Tamourt Sibté), Niger (Damagaram Takaya) and Mali (Agoufou). Zoom on Agoufou watershed with the Agoufou and Hombori meteorological stations (background: USGS, Landsat-8 image, 2015).