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Less rain, more water in ponds: a remote sensing study of the dynamics of surface waters from 1950 to present in pastoral Sahel (Gourma region, Mali)

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Abstract

Changes in the flood regime of ponds in the Gourma region from 1950 to present are studied by remote sensing, in the general context of the current multi-decennial Sahel drought. The seasonal and interannual variations of the areas covered by surface water are assessed using multi-date and multi-sensor satellite images (SPOT, FORMOSAT, LANDSAT-MSS, -TM, and -ETM, CORONA, and MODIS) and aerial photographs (IGN). Water body classification is adapted to each type of spectral resolution, with or without a middle-infrared band, and each spatial resolution, using linear unmixing for mixed pixels of MODIS data. The high-frequency MODIS data document the seasonal cycle, with an abrupt rise early in wet season and a progressive decrease in the dry season. They also provide a base to study the inter-annual variability of the flood regime, with sharp contrasts between dry years such as 2004 (low and early maximal area) and wetter years such as 2001 and 2002 (respectively high and late maximal area).The highest water level reached annually greatly depends on the volume, intensity and timing of rain events. However, the overall reduction by 20% of annual rains of the current period, compared to the 50' and 60', is concomitant with an apparently paradoxical large increase in the area of surface water, starting from the late 1980's. Spectacular for the two study cases of Agoufou and Ebang Mallam, for which time series covering the 1954-present period exist, this increase also reaches 98% between 1975 and 2002 for 92 ponds identified in central Gourma. Ponds with turbid waters and no aquatic vegetation are responsible for this increase, more pronounced to the north of the study zone. Possible causes of this change in surface water volume and regime are discussed based on differential changes in ponds dynamics related to the specifics in topography, soil texture and vegetation cover over the watershed. Changes in rain pattern and in ponds sedimentation are ruled out, and the impact of changes in land use, limited in the area, is found secondary, as opposed to what has often been advocated for in cultivated Sahel. Instead, major responsibility is attributed to increased runoff triggered by the lasting impact of the 1970–1980's droughts on the vegetation

and on the hydric system over shallow soils.

1 Introduction

The Sahel experienced an important decrease in precipitation during the second half of the 20th century, with severe droughts in 1972–1973 and again in 1983–1984 that have had a dramatic impact on the ecosystem and on the population living on the natural resources of this region (e.g. Dregne and Chou, 1992; Olsson, 1993; Hiernaux, 1996; Nicholson, 2001). Yet, in some part of the Sahel, the rainfall deficit did not lead to a decrease in surface runoff or in water-table level, as it happened in the wetter Soudanian and Guinean zones further south in West Africa. Indeed, evidence of an increase in water-table level has been reported in endorheic areas, such as in south-western Niger (Leduc et al., 2001). Along the same line, Mahé et al., 2003, 2005a outlined changes in hydrologic regime of rivers located in Burkina Faso, Mali and Niger, showing a discharge increase north of the 700 mm isohyets and therefore over northern Soudanian and southern Sahelian zones (see also the review by Descroix et al., 2009 and reference therein). Moreover, field observations in central and northern Sahel in Mali (Hiernaux unpublished data) suggest that, after the major droughts of the 1970's and 1980's, the flood of some temporary ponds extended longer over the dry season or even that some of these ponds became permanent. In southern Sahel, near Niamey (Niger), the increase in areas cleared for cropping, following the demographic expansion of rural population was suggested as a possible explanation for this phenomenon often referred to as the "Sahelian paradox": less precipitation leading to increase in run-off and water table recharge (Leblanc et al., 2008; Favreau et al., 2009). However, similar clearing to expand the area cropped also occurred in the Soudanian zone, without producing an increase in runoff (Descroix et al., 2009). Moreover, this explanation does not hold for pastoral areas in central or northern Sahel, where cropping has a very limited extend. The extent to which the Sahelian paradox applies to central and northern Sahel is still an open question. Yet, assessing and monitoring the recent changes in water resources, and understanding the processes of these changes are critical for the economy and livelihood of the Sahel population. Unfortunately, quantitative information on rainfall, surface water, aquifers, and land use is relatively scarce over this wide inland region

The aim of this work is to document and discuss the evolution from the mid twentieth century of surface water in the pastoral region of Gourma, in Mali. The study focuses on the evolution of the flood regime of ponds over the 1954–2007 period. Given the scarcity of in-situ quantitative information, flood regimes are studied through series of remotely sensed data. This requires combining remote sensing information acquired by different sensors and different support, satellite and aerial, to establish a coherent picture of the evolution of the ponds' regime. In particular, the average size of the ponds (at most a few hectares in the dry season) requires high resolution data to be used, which is hardly compatible with a suitable frequency in time-sampling. Indeed, ponds' areas strongly vary with time within a year (seasonal cycle) and display significant year-to-year variability in responses to rainfall variations. To date, attempts have been made to map ponds and to estimate ponds' area either at one date at a relatively high spatial resolution on the basis of one LANDSAT or SPOT-HRV image (Liebe et al., 2005; Lacaux et al., 2007) or at a lower resolution using time series of NOAA-AVHRR, SPOT-VGT or MODIS data (e.g. Gond et al., 2004; Haas et al., 2009; Verdin et al., 1996). Beside, the spectral response of surface water has received relatively little attention so far in this region, with a few exceptions like Lacaux et al., 2007. Combined to restrictions in sampling over time, the difficulty of using series of images differing in resolution and spectral bands probably explains why no monitoring has been carried out so far, despite surface water being such a critical resource in the Sahel.

After a short description of the site's characteristics and the available data sets in Sect. 2, classification methodologies used to outline water level in ponds are presented in Sect. 3. Section 4 provides an assessment of the classifiers' accuracy, as well as an analysis of the flood regime of the ponds, which changes over time are characterized. Finally, the observed change in hydrologic regime in the Gourma and its possible causes are discussed in Sect. 5.

2 Study area and data

2.1 The study site

The Gourma region is located in Eastern Mali within the loop of the Niger River down to the border with Burkina-Faso. It extends over the Sahelian bioclimatic gradient from 550 mm annual rainfall in the south to 150 mm in the north. Most of the ponds monitored in this study are located in the centre of the Gourma region, within the study site, referred as 'supersite', of the AMMA project (15.58–15.13° N; 1.75°–1.33° W) with mean annual rainfall ranging between 300 and 450 mm (Mougin et al., 2009). As elsewhere in the Sahel, the climate is tropical semi-arid with monsoonal rains falling between late June and mid September followed by a long dry season (Frappart et al., 2009). Rainfall recorded at Hombori display the general pattern of the Sahel drought , with a sharp contrast between the 50's and the 80's (Fig. 1). Indeed, rainfall of most years from 1970 onwards stand below the average over the whole series (375.2 mm±110.8 from 1936 to 2008) with average rainfall dropping of 20% prior (422.2 mm) and since (336.2 mm) 1970. Mean air temperature recorded at Hombori is 30.2°C. The highest monthly value is observed in May (42°C) whereas the lowest one is found in January (17.1°C).

The Gourma region is part of large sedimentary basin which bedrock is mainly composed of Precambrian sandstones and schists eroded in a peneplain only surmounted by a few hard sandstone plateaus. The eroded slopes are locally capped by an iron pan inherited from humid periods of the quaternary, while a bit more than half of the landscape is covered by fixed sand dunes inherited from the arid periods of the quaternary. In valleys, a web of alluvial and lacustrine plains is also inherited from the humid periods, and has been segmented by the sand dunes cutting across valleys. The Gourma region is globally endorheic, but it harbours two hydric systems arranged in a mosaic as shown by the subset represented by the LANDSAT image in Fig. 2.

On the sandy soils (58% of the area, appearing in red–brown-green on the LANDSAT scene in Fig. 2), the endorheic system operates at short distance with limited sheet run-off from dune slopes to inter-dune depressions feeding ephemeral puddles or ponds not considered in this study. On rock and iron pan outcrops, associated shallow soils and low-land fine-textured soils (42% of the area altogether, appearing in blue-white in Fig. 2), the endorheic system operates over much larger distances with concentrated run-off feeding a structured web of rills ending in one or several interconnected ponds, which flood regime is the object of the study (contoured in yellow on the LANDSAT scene in Fig. 2). The position of the pond along the hydric web, its geomorphology and flood regime distinguish main categories (Ag Mahmoud, 1992). Upstream, there are small ponds generated by a local obstacle to the water run-off, such as a bar of hard rock or a sand dune. There are a few case of partially artificial ponds that man historically deepened by digging, the extracted material being deposited in a crescent shaped dam to the downstream side (Taylalelt ponds for example, see Fig. 2). Ponds also occur along the main valleys when the stream bed gets locally deeper, often at confluence of streams (Ekia, Zalam-zalam, In Gariaten), or because of a slow down of the stream flow due to a physical obstacle, either rocky (Massi, Toundourou) or sandy (Gossi, Adjora). Attempts to control the out flow of these two last ponds have been made by building concrete levels at the downstream outlet in 2006, their impact on the pond flood is not considered in this paper. Down stream, final ponds are either located at the bottom of the alluvial or lacustrine plain (Kelma, Fossa, Alzouhra), or else at the foot of a natural dam most often due to sand dunes cutting across the valley (Agoufou, Dimamou, Doro). In the first case, ponds are often surrounded by temporarily flooded alluvial plain which loamy clay soils are partially colonised by open forest of adapted trees such as *Acacia seyal* (Kelma, In Orfan) *Acacia nilotica* (Ouart Fotou) or *Anogeissus leiocarpus* (Darawal). These flooded plains are not included in this study that only considered ponds that generally keep water beyond October with a maximum flood depth superior to 50 cm. The flooded area varies from a few hectares to a few thousand hectares. Most of these ponds are temporary flooded, but there are a few permanent lakes such as Gossi and more recently Agoufou. Some of these ponds or lakes also feed local shallow water tables that complement the water resources for the Gourma population and their livestock in a region otherwise deprived of continuous aquifer (Défossez, 1962).

The vegetation of the Gourma region is typical Sahelian with an herbaceous layer almost exclusively composed of annual plants, among which grasses dominate, and scattered bushes, shrubs and low trees (Hiernaux et al., 2009). Almost continuous on sandy soils, except for a few deflation patches and bare dune crests, the herbaceous layer is highly discontinuous on shallow soils and clay plains, living large area bare of vegetation prone to run-off. The density and canopy cover of woody populations are low in average (Hiernaux et al., 2009) however there are concentrations of woody plants along drainage lines, around ponds, in the inter-dune depressions and also on shallow soils, with the narrow linear thickets set perpendicular to the slope known as "tiger bush" (Hiernaux and Gerard, 1999). These thickets live on the water and nutrients harvested on the upstream bare soil impluvium, and their development efficiently limit run-off further downstream. The economy of rural population is mostly pastoral, with various livestock management practices and seasonal mobility strategies (Boudet et al., 1971). In the southern half of the Gourma region, up to the surroundings of Hombori mountains, husbandry is associated to some staple crops, mostly millet on sandy soils, and sorghum on finer textured soils. Yet, total land cropped in southern Gourma extends on less than 3% of the land (Zin et al., 2009) and has not much expanded since the early 1970's (Marie and Marie, 1974; Bourn and Wint, 1985).

2.2 Data

Different types of images, with different spectral, temporal and spatial resolution, have been employed to monitor the ponds' area over the longest possible period. Before the era of multi-spectral data acquisition with sensors onboard satellites (the first LANDSAT satellite was launched in 1972), images were acquired with airborne cameras or space-borne panchromatic sensors. Series of images from LANDSAT, SPOT, FOR-

MOSAT, CORONA, MODIS have been collected over the Gourma supersite as well as aerial photograph, as shown on Fig. 3, and detailed in Table 1. Two ponds, Agoufou and Ebang Mallam, are the two main "case studies" with intensive acquisition of high resolution data, whereas spatial extension over the central Gourma is obtained from less frequent high resolution data.

The temporal resolution of the available images is a major issue for this type of long-term study. Indeed, ponds are highly seasonal in the Sahel, therefore it is crucial to acquire images at similar periods of the seasonal cycle. This seasonal cycle is typically monitored with images every week or at least every other week. Unfortunately, satellites with a daily or weekly repeat-pass frequency have a coarser spectral resolution than those with 30 days frequency transit, and a compromise has to be found between temporal and spatial resolutions. The coarser resolution within the data set used during the study is of 250 m for MODIS images and the smallest pond that could be classified with these images should have at least 25 ha area. All the other images employed have a spatial resolution finer than 30 m (Table 1), allowing thereby mapping smaller ponds, down to 1 ha. Also, the spectral resolution, namely the ability of the sensor to differentiate bands in different wavelengths, widely varies from one sensor to another.

SPOT, LANDSAT and FORMOSAT images were already registered in the UTM zone 30 North projection using the WGS84 datum, whereas MODIS images (MOD09Q1, 250 m resolution NIR and red reflectance) were projected in sinusoidal projection. All satellite data have been radiometrically corrected, but neither atmospheric nor viewing angles effects have been taken into account. The CORONA and aerial photographs have been registered only locally, namely around a specific pond, using a registered SPOT-4 panchromatic image with a 5 m×5 m pixel size from 2005 as the reference. To this end, tie points, mostly located on trees or rocky features, have been used and a second degree polynomial transformation has been applied to each image.

3 Methods

Since the spatial and spectral resolutions of the available satellite images are very heterogeneous, it has not been possible to use the same classification algorithm for all images. Instead, one method had to be defined for each kind of data sets. Except for LANDSAT images, for which a supervised classification has been applied, all other images have undergone classifications using thresholds on pixels' reflectance or indexes values. Table 2 summarizes the indexes used for the classifications. The Normalized Difference Vegetation Index (referred to as NDVI, Eq. (2) in Table 2), introduced by Rouse et al., 1973, is usually used to monitor the amount of vegetation on bare soils. Puech 1994 used it to detect water bodies, and especially ponds with suspended sediment load. However, it does not allow distinguishing vegetation on bare soil from aquatic vegetation. That is why Lacaux et al., 2007 have defined the Normalized Differenced Pond Index (NDPI, Eq. (4) in Table 2), based on the fact that water has a very low reflectance (about 15%) in the middle infrared wavelength. A Normalized Difference Turbidity Index (NDTI, Eq. (3) in Table 2) has also been used to evaluate the level of turbidity of open water. It takes heed of the fact that turbid water tends to respond spectrally like bare soils, with low reflectance in the green wavelength, but high in the red one.

3.1 Spectral signatures of sahelian ponds

As suggested by Lacaux et al., 2007 for the ponds of the Ferlo region (Senegal), ponds in the Gourma can be sorted into 2 categories, showing a distinct spectral signature. In the following, these two types of ponds are labelled according to the colour in which they appear on a classical Red-Green-Blue false colour composite Near Infrared/Red/Green spectral bands:

1. "blue" ponds, (Fig. 4a), are very turbid and free of vegetation, with a low reflectance in the middle infrared wavelength. Flood in blue ponds can easily be

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detected because of the strong negative values of NDPI. Their spectral signature is invariant, whether during the rainy or dry season.

2. "red" ponds, (Fig. 4b), are less turbid and at least partially covered with various aquatic plants, with high reflectance in the near infrared wavelength as well as high values of NDVI. Their spectral responses are therefore very similar to that of vegetation, which makes them more difficult to identify. Reflectance in the middle infrared are not as low as for the "blue" ponds because of partial vegetation cover over the water surface, which reduce the wave absorption. Aquatic vegetation includes dense aquatic savannas dominated by sedges such as *Cyperus maritimus*, or grasses such as *Oriza barthii*, *O. longistaminata*, *Echinochloa stagnina*, *Panicum subalbidum*, that all spread in shallow water at the edge of the pools or on islands. In deeper ponds aquatic vegetation is often limited to patches of plants that are rooted in the mud of the pond bed but have specialised organs such as floating stems (*Nelsonia canescens*), or leaves (*Nymplea lotus*, *N. maculata*, *Eichhornia natans*), dissected leaves that remain photosynthetically active under a few centimetres of water (*Ottelia ulvifolia*, *Najas pectinata*, *Ramphycarpa fistulosa*) and a few floating species (*Nymphoides indica*, *Utricularia stellaris*, *Azolla pinnata*), (Boudouresque, 1995). In addition to herbaceous aquatic plants temporary, flooded ponds can harbour some woody plants from species standing seasonal flood such as *Ziziphus mauritiana*, *Acacia nilotica* and *Mitragyna inermis*. After the first rains, the "red" ponds behave as "blue" ponds and turn "red" as aquatic vegetation develops later in the rainy season.

These different spectral signatures have been accounted for in the classification process described for each sensor in the following subsections.

3.2 Classification of SPOT-4 images (HR-VIR sensor)

The reflectance value for "blue" ponds is very low in the middle infrared wavelength, and the NDPI index is markedly negative. SPOT-4 imaging, with its middle infrared channel and its high spatial resolution is therefore very convenient to map the flood for this category of pond. As suggested by Lacaux et al., 2007; the classification of ponds was performed, using a decision tree, putting a first threshold on the NDPI value and a second one on the reflectance in the middle infrared wavelength. To determine thresholds values automatically, a region of interest was defined in the centre of the flooded pond to be outlined. The average values of the NDPI and the MIR band within this region were then computed, and a tolerance was applied to those values to define the thresholds used for the classification (namely ±0.1 for the index values and ±5% for the reflectance values).

3.3 Classification of FORMOSAT images

FORMOSAT images do not have a MIR band. Alternative classification algorithm is thus needed to outline ponds. A threshold on the NDVI was first applied, using a decision tree, then a threshold on the green band and finally one on the NDTI. These thresholds were computed for each image and for each pond individually in a similar way as for SPOT-4 images, that is to say by computing an average value (for NDVI, Green and NDTI) in the centre of the pond and adding a tolerance to the result to obtain the thresholds above/below which a pixel was classified as “pond”.

3.4 Classification of LANDSAT images

LANDSAT images have the advantage of a wide ground coverage (Figs. 2 and 3), as well as a good spectral resolution, especially for TM and ETM images with two channels in the middle infrared wavelengths which are very useful to detect water bodies. In order to compare the area flooded in the ponds of central Gourma in 1975 and in recent years, a supervised classification was performed on the MSS scene of the 14/09/1975. Following Liebe et al., 2005, up to nine types of flooded surfaces were identified, depending on the turbidity of the water and the presence or absence of aquatic herbs, or woody plants. Theses types were classified separately and then gathered into either turbid or clear water ponds. Temporary flooded plains on fine textured soil, with or without tree and vegetation cover were also classified and kept separated from ponds. A similar supervised classification scheme was applied to ETM images of 03/09/2002 and 29/10/1999 to obtain a regional evaluation of the water-covered surface.

3.5 Classification of MODIS images

Given the coarse spatial resolution (250 m) and the spectral resolution of MODIS images, (red and infrared channel only for this resolution), small ponds and "red" ponds are not monitored. In addition, since a pixel surface is equivalent to almost 7 ha, a classification based on pure pixels only may lead to a rough approximation of the effective pond's surface for most ponds in the Gourma. Therefore, it was necessary to consider a sub-pixel classification to refine the result. The algorithm, which has been designed, consists first in defining a region of pure open water pixels and one of "dry" pixels (which can either be vegetation on bare soils or rocky outcrops) surrounding the pond to be outlined. For each of these two regions, spatially averaged values are computed for both original channels (red and infrared) and then the NDVI. All pixels with a NDVI value lower than the average of the "pure water" region are classified as "flooded pond". Conversely, pixels with NDVI values higher than average over "dry soil" are classified as "dry soil". The pixels with NDVI in between are considered mixed pixel. The fraction of open water is assessed by the following linear un-mixing relationship:

$$\mathrm{NDVI}_{\mathrm{mixed}} = k \cdot \mathrm{NDVI}_{\mathrm{dry}} + (1-k) \cdot \mathrm{NDVI}_{\mathrm{water}} \quad (1)$$

where k is a linearity coefficient ($0<k<1$). The proportion of water in a mixed pixel is given by ($1-k$). This proportion is computed for all mixed pixels and summed to the pure open water pixels to assess the total pond area.

3.6 Classification of panchromatic images

Panchromatic images include aerial photographs as well as CORONA images, acquired in a mono-spectral mode. This prevents automatic detection of water bodies, which may be confused with rock outcrops or bare sands (Leblanc et al., 2008). Ponds were therefore outlined manually by an operator, based on knowledge of ground truth and based on the comparison with the reflectance of the surroundings (texture, glint). As the result might be operator dependant, the delimitation process was made by different persons.

4 Results

4.1 Assessments of the classifications

For most high spatial resolution images (CORONA, aerial pictures, FORMOSAT, SPOT and LANDSAT-MSS), the assessment of the classification is done visually, by overlapping the classified pond's contour with the corresponding image. For LANDSAT TM and ETM, images, the accuracy of the maximum likelihood classifier is evaluated by comparing classified data with an independent set of well characterized areas resulting from field studies (Hiernaux unpublished). These classifications proved to be quite precise, with an overall accuracy ranging from 97% to 99%, depending on the images. An example of the accuracy assessment is reported in Table 3.

These evaluations are not possible in the case of MODIS images, for which a 200 ha pond is represented by a few pure pixels (less than 10) and several mixed pixels that make the contour difficult to visually identify. Thus, surface variations computed from MODIS images have been compared to the results from high spatial resolution images, namely the FORMOSAT and SPOT times series in 2005, 2006 and 2007. The main outcomes are presented in Fig. 5. During the rainy season, the variation of the flooded area derived by MODIS compare well with the area assessed with the other sensors, with a difference of less than 10%.

The agreement is not very good at the end of the dry season, with a relative difference reaching up to 78% in the worst cases. This can be explained by the fact that during the drying phase, the size of the ponds decreases so that the number of pixels of “pure water” sharply declines. For most ponds, the classifications at the end of the dry season are only based on mixed pixels and are therefore less accurate. Moreover, some ponds, like Ebang Mallam, split into several small ponds, which size may be smaller than the spatial resolution of MODIS. This is in line with previous studies using moderate and low resolution sensors (Verdin et al., 1996; Gond et al., 2004; Haas et al., 2009), which concluded that surface estimation is accurate above a given threshold of a few ha or tens of ha, allowing pure pixels to be present. Ponds’ size at the end of the wet season, typically October to December, is therefore preferred to carry out the analysis on the long term changes.

4.2 Seasonal variability

Rainfalls over the Gourma depend on the West African Monsoon, with rains usually starting in June and ending in late September, sometimes up to October (Frappart et al., 2009). The hydrologic regime of the ponds is closely related to the rainfall distribution and its spatial and inter-annual variability. The eight year of MODIS data allow monitoring the ponds seasonal cycle, as shown in Fig. 6 for Agoufou and Ebang Mallam. Two phases can be distinguished:

1. The rising up of the flood fed by surface runoff. There is an abrupt rise of the pond area generally occurring between June and July followed by marginal changes during the rest of the rainy season (August and September).

2. The decrease of pond’s area is mostly due to evaporation, with some infiltration and, to a lesser extent to the use by human for drinking, irrigation and livestock watering (Desconnet, 1994). Most ponds in the Gourma dry up between November and May. Only a few (Gossi, see Fig. 2 also Benzéma, which is west of the LANDSAT scene) were permanent until the 1990’s (Ag Mahmoud 1992) but since, additional ponds (Agoufou, Ebang Mallam for example) became permanent.

4.3 Inter-annual variability

The surface of the ponds is influenced by the inter-annual variability of the rainfall, both by the volume and intensity of the rain events (i.e. rainfall deficit, droughts) and by their timings (i.e. delay of the first rains which may occur as late as late July). The variations of the surface of the Agoufou pond inferred from 2000–2007 MODIS data (Fig. 7) show a linear relation with precipitation. The pond's area reached its maximal size at the end of October 1999, which was an unusually wet year for the 1980–2000 period, (see Fig. 1), whereas it was minimum in 2004, a year characterized by a strong rainfall deficit over the Gourma, close to the major droughts of the 70' and 80'. However the values of the pond's surface do not appear to be widely scattered over the last 10 years: for cumulative rainfall ranging from 300 mm to 400 mm, the surface of Agoufou pond falls between 150 ha and 230 ha and Ebang Mallam (not shown) falls between 300 ha and 450 ha.

4.4 Changes in the ponds' hydrologic regime

The analysis reported above provide a range of seasonal values of the flood surface of the ponds that allows the interpretation of their comparison with the few data available for the historical period (single points in Fig. 6). Each historical data can be compared to pond's surface at the same time of year and for similar rainfall amount. The evolution of the annual maximum of the flood surface since the 1950's is remarkable (Figs. 6, 7 and 8). Even when the seasonal and inter-annual variability is taken into account for a given pond, the area of open water during the wet period, that preceded the drought of the 1970's and 1980's is much smaller than nowadays (Figs. 6 and 8). For example, the surface flooded at Agoufou and Ebang Mallam only reached a few hectares in the sixties and seventies, and both ponds were drying up a couple of months after the last rains. For approximately the same cumulative rainfall value of 375 mm, the size of the water surface is much larger nowadays than what it used to be in 1965 or 1996 (Fig. 7). Likewise, to reach a similar size, Ebang Mallam pond needed twice more rainfalls in

1966 than in 2004. From 1990 though, the area of these ponds appear to increase and open water remains during the whole dry season. The swelling of the ponds flood do not match the onset (early 1970's) nor the peak of the drought (mid 1980's). It did not coincide either with the wetter years of (1991, 1994, 1996 and 1999) but preceded them, starting in the late 1980's with open water remaining during the whole dry season in both ponds from1990 onwards. The size of both ponds continued to grow after 1990 to reach the present regime.

4.5 A regional phenomenon

The supervised classification of flooded and moist soil surface in September 1975 and September 1999 and 2002 allowed the detection of changes in ponds' area for 92 ponds located in the overlapping area of the three LANDSAT images covering the centre of the Gourma region (Fig. 3). All together, the flooded area of these ponds reached 12 441 ha in 1975, 20 321 ha in 1999 and 23 119 ha in 2002, thus an overall increase by 98% over the 1975–2002 period of time. The following analysis focuses on the 2002–1975 paired classifications, since these two years are closer in terms of precipitation and span a longer time-period. The comments however are qualitatively valid for the period 1975–1999 also, since a large part of the changes already occurred in 1999 or before. Despite the overall 98% surface increase between 1975 and 2002, 17 ponds had no flood increase, and the rate of increase of the other 75 significantly varied between ponds. When grouped by large geographic zones: erosion surfaces of northern Gourma, of central Gourma, and southern plains (Fig. 3), it appears that ponds' flood spread at increasing rates from south to north (Fig. 9). Moreover, this expansion is mostly caused by the increase of area flooded with turbid waters ("blue" ponds), while the area flooded with clear waters ("red" ponds) actually declined slightly both in centre and southern Gourma. In fact if the radiometric behaviour of the "red/blue ponds" can be associated to presence/lack of green vegetation, the two radiometric behaviour can also be associated to the turbidity of the water, generally higher, and remaining high during the dry season, in the "blue" ponds. The two criteria are not independent as high turbidity impedes the development of herbaceous aquatic plants. The turbidity of the water is firstly determined by the geological nature of the watershed, schist producing more loam and clay alluvium than do sandstone and hard pan. Secondarily, the speed and the duration of the run-off flow, both function of the size and the altitude profile of the watershed will either reinforce (fast and short duration flow) or attenuate turbidity (slow and long duration flow, especially if there are relay ponds where some of the mud load can be deposited before reaching the final pond). Finally some ponds have changed behaviour over years, turning from "red" pond behaviour to "blue" pond behaviour following a large increase in the volume of flood and water turbidity. This is due to a structural modification of the hydric system with the shortcut of some of the relay ponds upstream, acceleration of the flood speed by deepening of the channels, and, like in the case of Agoufou, expansion of the watershed by capture of a neighbour watershed that till the late 1980's was only feeding the ponds of Sabangou and Taylalelt. Thus, the increase in pond surface is a general phenomenon, which varies in nature and rhythm depending on pond's environment and hydric system.

5 Discussion

5.1 Technical considerations

The large time span over which ponds were monitored brought the main challenge of this study. It required the combination of information from aerial photos and satellite images coming from a wide variety of sensors. The objective was to obtain temporally coherent information on the flood surface of the ponds despite the different quality and the different spectral/temporal and spatial resolution of those documents. High spatial resolution images, such as SPOT or FORMOSAT, as well as LANDSAT, give access to accurate ponds surface evolution over time, especially when they include a middle infrared channel. Panchromatic photos or images do not allow automatic detection of pond and hence photo-interpretation and texture differences have been used to identify

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ponds. In the Gourma region, the changes of ponds over time were so important that these methods were accurate enough. When using coarse resolution images (MODIS), a critical size was identified. The algorithm developed to include mixed pixels in the assessment of the flooded area, is less satisfactory when the area flooded gets inferior to 25 ha, but proves accurate for larger water bodies. Overall, the magnitude of the error made on the assessment of the flooded area of the ponds, at least for the "blue" ponds, which flooded area is superior to 10 hectares, is very small compared to the observed large increase in annual maximum of area flooded in these ponds between the 1950's and present time.

5.2 A paradoxical dynamics

The pond's area expansion between 1975 and 2002 is due to an increase of the area covered by turbid water (397%) while the area of clear water slightly decreased (–2%). Yet, increase in pond's surface may have different causes.

In the Gourma, increase in rainfall amount (Fig. 1) as well as increase in daily rainfall intensity can be ruled out. Indeed, Frappart et al., 2009 did not find any trend in rain per rainy day over 1950–2000. They found, however, a possible trend towards more intense rains (rain per rainy day) in 2000–2007 compared to the previous decades. Yet, this possible increase occurred well after pond's increase in area (starting in the late 80' and early 90').

Increase of pond's surface might also be caused by sediments deposition. Sediment deposition in Gourma ponds over the study period certainly increased with increasing run-off but it should play a minor role in the area expansion of the major ponds because of the long time required for coarse alluvium to reach the outlet in this overall flat landscape, and because of the large increase in volume of water involved.

Increased surface run-off is therefore the most plausible factor causing the observed increase of the pond area in the Gourma. This is in line with the increased run-off observed in other Sahelian regions (Mahé et al., 2003, 2005a, b; Descroix et al., 2009). Although it is less easy to conclude for "red" ponds, which flood area is less easy to assess by remote sensing, it seems that "red" ponds did not increase as much as "blue" ponds over the same period of time. These remote sensing outputs are also confirmed by field observations: no death of woody plants in the deepest part of the pond following the anaerobic conditions due to a prolongation of the flood period was observed in "red" ponds contrary to observations for "blue" ponds; no change was observed, either on the shore line, nor on the topographic profile of the red ponds. Would this mean that surface runoff did not increase that much in the watersheds that are feeding the "red" ponds? These watersheds concentrate in the southern part of the Gourma, especially all the watershed spreading from the hard sand stone plateaux near Hombori but there are also some red ponds in northern Gourma, including large ones such as Doro and Karouassa (Fig. 2). Yet the fact that a number of the "red" ponds are located along a stream could explain their behaviour even under the hypothesis of increased run-off. Indeed, increased run-on could be evacuated as a downstream discharge that could be absorbed in the swelling of the flood plains without marked effect on the flood level in the downstream ponds. This could in turn explain the expanding woody plant population at the edges of the forest plains observed since the 1990's in most plains of the Gourma (Hiernaux et al., 2009).

5.3 What are the possible causes of the increase in surface runoff?

It is noteworthy that the "blue" ponds, especially those which increased most since the 1980's, are not located in the area where crops concentrate. In addition, most ponds in the depression that surrounds the Hombori mountains, area under strong anthropogenic pressure, are of "red" type and have not increased size much. As a consequence, nor the limited increase in area cropped, nor the intensity of grazing and trampling by livestock maintained longer and in higher number at the vicinity of settlements, can be advocated as leading factor of the increased run-off, as suggested for other regions of the Sahel such as in South-West Niger (Leblanc et al., 2008, Favreau et al., 2009). Indeed, crop fields (less than 3% of total land area) are confined to sandy soils that only marginally contribute to run-off. In addition to crops expansion, degradation of vegetation cover may also be caused by wood harvesting to meet the needs of local population for domestic use. During the most severe years of the droughts (1972–1973 and 1983–1984), some people ended in harvesting and selling wood to buy millet in order to face the deficiency of their own millet crops. But again, the Gourma does not seem to be concerned by the aspect of human deforestation. Benjaminsen (1996) studied the evolution of woody population over the Malian Gourma, between 1955 and 1985, and came to the conclusion that the significant decrease in the number of trees in this area is only due to the drop in rainfalls, and that the domestic use of firewood could not be involved. Since then, the monitoring of woody plant populations from 1984 to present in the Gourma concludes to an overall increase both in density and cover of the woody population (Hiernaux et al., 2009).

There are important exceptions to this situation, however, for the woody population located on shallow soils over rock or hard pan outcrops, which are the landscape units generating most of the run-off. These woody plant populations have experienced a continuous decline in density and cover, associated to a profound change in structure. The "tiger bush" arrangement, with dense thicket set perpendicular to the slope (Hiernaux and Gérard, 1999), have either been decimated or completely dismantled and in this case replaced by totally different arrangement in which scattered shrubs settled along the rills and thus along the slopes. While the vegetation of rangelands set on sandy soils and on lowland clay soils monitored in the Gourma revealed very resilient to the drought, with a fast regeneration (2–5 years to reclaim production) of the herbaceous layer and a slower one for woody plants (10–25 years to reclaim production), that of the shallow soils did not recover from the drought 25 years later. Herbaceous layer and woody plants only recovered partially since mid 1990's in scattered areas along the drainage lines and on sand deposition, offering little resistance to run-off. Yet, these shallow soils over rock and hardpan outcrops are the main source of run-off to the ponds and could explain their flood increase. Further, the differential increase of the pond's flood could be related to the relative extend of these soils within the pond watershed. Whether a future return to normal precipitation in the next decades could cause a reversal of pond's size and regime, triggered by a complete recovering of vegetation on the shallow soil, is an important question for pastoral Sahel, which deserves dedicated monitoring.

6 Conclusions

Changes in the water regime of ponds in the Gourma region was established through the use of multi-date and multi-sensor satellite images. The actual classification process to outline the flood level of ponds has to be adapted to fit each type of spectral resolution (lack or presence of a middle infra-red band, panchromatic image) and spatial resolution (for a resolution coarser than 30 m mixed pixels had to be included in the assessment of flood surface of ponds).

The outcomes enabled to document the seasonal in inter-annual flood dynamics in ponds with the rising of the flood related to rainfall distribution followed by a drying up during the dry season for a majority of the ponds in the Gourma. The analysis allowed quantifying the change in the flood regime starting in late 1980's for two ponds (Agoufou and Ebang Mallam) that experienced a spectacular increase in flood level and duration, evolving from temporary to permanent ponds. Indeed, for a same total rainfall of 380 mm at the end of October, the size of the pond of Agoufou has been multiplied threefold between 1996 and 2003. The flood evolution of these two ponds is at the larger end of the general behaviour of Gourma ponds. Yet, there is an overall trend of flood increase from the 1950's till present causing the flooded area of ponds observed at the peak of the flood to double in average from 1975 to 2002.

The causes of the changes in flood regime of ponds are discussed in relation to their geograhic location, the particularities of the watershed feeding them, and the dynamics of the radiometric characteristics of their flood. The possible impact of cropland expansion and intensification of forestry and pastoral use are discussed and considered secondary. Instead, it is argued that the lasting impact of the climatic droughts of the 1970's and 1980's on the herbaceous and woody plant vegetation over the shallow soils on rock and hard pan outcrop, and its consequences on the hydric system, are the main causes of this spectacular phenomenon.

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References

Ag Mahmoud, M.: Le haut Gourma Central (second edition), edited by: Le Floc'h, R. CEFE/CNRS, Montpellier, 133 pp., 1992.

Benjaminsen, T. A.: Bois-énergie, déboisement et sécheresse au Sahel: le cas du Gourma malien. *Sécheresse*, 7, 179–185, 1996.

Boudet, G., Cortin, A., and Macher, H.: Esquisse pastorale et esquisse de la transhumance de la région du Gourma (Mali), DIWI, Essen, Germany, p. 120, 1971.

Boudouresque, E.: La végétation aquatique du Liptako (République du Niger). Thèse Univ. Paris XI, Orsay, France, p. 391, 1995.

Bourn, D. and Wint, F.: Wet season distribution and abundance of livestock populations and human habitants in the Gourma region of Mali. Resource Inventory and Management, St. Helier, Jersey, UK, p. 53, 1985.

Defossez, M.: Contributions à l'étude géologique et hydrogéologique de la boucle du Niger. Mémoire BRGM, 13, p. 174, 1962.

Desconnets, J.-C.: Typologie et caracterisation hydrologique des systèmes endoreiques en milieu Sahélien (Niger-degré carré de Niamey), Thèse Université de Montpellier II, 326 pp., 1994.
Descroix, L., Mahé, G., Lebel, T., Favreau, G, Galle, S., Gautier, E., Olivry, J. C., Albergel, J., Amogu, O., Cappelaere, B., Dessouassi, R., Diedhiou, A., Le Breton, E., Mamadou, I., and Sighomnou, D.: Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: a synthesis, J. Hydrol, doi:10.1016/j.jhydrol.2008.12.012, in press, 2009.
Dregne, H. E. and Chou, N. T.: Global desertification : dimensions and costs, in: degradation and restoration of arid lands, edited by: Dregne H. E., Texas Tech Univ., Lubbock, Texas, 249–82, 1992.
Favreau G., Cappelaere, B., Massuel, S., Leblanc, M., Boucher, M., Boulain, N., and Leduc, C.: Land clearing, climate variability, and water resources increase in semiarid south-west Niger, Africa: a review, Water Resour. Res., 45, W00A16, doi:10.1029/2007WR006785, 2009.
Frappart, F., Hiernaux, P., Guichard, F., Mougin, E., Kergoat, L., Arjounin, M., Lavenu, F., Koité, M., Paturel, J.-E., and Lebel, T.: Rainfall regime across the Sahel band in the Gourma region, Mali, J. Hydrol., doi:10.1016/j.jhydrol.2009.03.007, in press, 2009.
Gond, V., Bartholome, E., Ouattara, F., Nonguierma, A., and Bado L.: Surveillance et cartographie des plans d'eau et des zones humides et inondables en régions arides avec l'instrument VEGETATION embarqué sur SPOT4, Int. J. Remote Sens., 25(5), 987–1004, 2004.
Haas, E. M., Bartholomé, E., and Combal, B.: Time series analysis of optical remote sensing data for the mapping of temporary surface water bodies in sub-Saharan western Africa, J. Hydrol., doi:10.1016/j.jhydrol.2009.02.052, in press, 2009.
Hiernaux, P.: The crisis of sahelian pastoralism: ecological or economic? Overseas Development Institute, Pastoral Development Network, 39a, p. 20, 1996.
Hiernaux, P., Diarra, L., Trichon, V., Mougin, E., Soumaguel, N., and Baup, F.: Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali), J. Hydrol, doi:10.1016/j.jhydrol.2009.01.043, in press, 2009.
Hiernaux, P. and Gérard, B.: The influence of vegetation pattern on the productivity, diversity and stability of vegetation: the case of the 'brousse tigrée' in the Sahel, Acta Oecol., 20(3), 147–158, 1999.
Lacaux, J. P., Tourre, Y. M., Vignolles, C., Ndione, J. A., and Lafaye, M.: Classification of ponds from high-spatial resolution remote sensing: Application to Rift Valley Fever epidemics in

Senegal, Remote Sens. Environ., 106, 66-74, 2007.
Leblanc, M., Favreau, G, Massuel, S., Tweed, S, Loireau, M., and Cappelaere, B.: Land clearance and hydrological change in the Sahel: SW Niger, Global Planet. Change, 61(4), 135–150, 2008.
Leduc, C., Favreau, G., Shroeter, P.: Long term rise in a Sahelian water-table: the Continental Terminal in South-West Niger, J. Hydrol., 243, 43–54, 2001.
Liebe, J., van de Giesen, N., and Andreini, M.: Estimation of small reservoir storage capacities in a semi-arid environment, A case study in the Upper East region of Ghana, Phys. Chem. Earth, 30, 448–454, 2005.
Mahé, G , Leduc, C., Amani, A., Paturel, J. E., Girard, S., Servat, E., and Dezetter, A.: Augmentation du ruissellement de surface en région soudano-sahélienne et impact sur les resources en eau, Hydrology of Mediterranean and Semiarid regions, edited by: Servat, E., Najem, W., Leduc, C., and Shakeel Sci, A., Proc. Conf., Montpellier, France, 003, IAHS Pub. no. 278, 215–222, 2003.
Mahé, G., Olivry, J. C., and Servat, E.: Sensibilité des cours d'eau ouest africains aux changements climatiques et environnementaux: extrêmes et paradoxes. Regional hydrological impacts of climatic change – hydroclimatic variability, proceedings of symposium S6 held during the seventh IAHS scientific Assembly at Foz de Iguaçu, Brazil, April 2005, IAHS Pub. no. 296, 169–177, 2005a.
Mahé, G., Paturel, J. E., Servat, E., Conway, D., and Dezetter, A.: The impact of land use on soil water holding capacity and river flow modelling in the Nakambe River, Burkina Faso, J. Hydrol., 300, 33–43, 2005b.
Marie, J. and Marie, J. La region de Hombori. Essais de géographie régionale en zone sahélienne. Mèm. Maitrise, Inst. Géographie, Univ. Rouen, France, 300 pp., 1974.
Mougin, E., Hiernaux, P., Kergoat, L., Grippa, M., de Rosnay, P., Timouk, F., Le Dantec, V., Demarez, V., Lavenu, F., Arjounin, M., Lebel, T., Soumaguel, N., Ceschia, E., Mougenot, B., Baup, F., Frappart, F., Frison, P. L., Gardelle, J., Gruhier, C., Jarlan, L., Mangiarotti, S., Sanou, B., Tracol, Y., Guichard, F., Trichon, V., Diarra, L., Soumaré, A., Koité, M., Dembélé, F., Lloyd, C., Hanan, N. P., Damesin, C., Delon, C., Serça, D., Galy-Lacaux, C., Seghieri, J., Becerra, S., Dia, H., Gangneron, F., and Mazzega, P.: The AMMA-CATCH observatory site in Mali: relating climatic variations to changes in vegetation, surface hydrology, fluxes and natural resources, J. Hydrol., accepted, 2009.
Nicholson, S. E.: Climate and environmental change in Africa during the last two centuries,

Clim. Res., 14, 123–144, 2001.
Olsson, L.: On the causes of famine: drought, desertification and market failure in the Sudan, Ambio, 22, 395–403, 1993.
Puech, C.: Plans d'eau sahéliens et imagerie SPOT: inventaire et évaluation des capacités d'exploitation. Colloque international "Eau, Environnement et Développement", Nouakchott, 20–22 March, 1994.
Rouse, J. W., Haas, R. H., Schell, J. A., and Deering, D. W.: Monitoring vegetation systems in the Great Plains with ERTS, Third ERTS Symposium, NASA SP-351 I, 309–317, 1973.
Verdin, J. P.: Remote sensing of ephemeral water bodies in Western Niger, Int. J. Remote Sens., 17, 733–748, 1996.
Zin, I., Zribi, M., André, C., Dessay, N., Guibert, S., Hiernaux, P., Kergoat, L., Lacaze, R., Mascle-Le Hgarat, S., Ottlé, C., Saux-Picart, S., and Seghieri, J.: Land cover assessment on the three AMMA experimental sites from SPOT/HRVIR data., Int. J. Appl. Earth Observ. Geoinformation, submitted, 2009.

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Table 1. Characteristics of the satellite and aerial images used in the study.

Satellite	Sensor	Spatial resolution	Spectral resolution	Year of acquisition	Ground coverage	Number of images
SPOT 1	HRV	20 m	G, R, NIR	1990	60 km×60 km	2
SPOT 4	HRVIR	20 m	G, R, NIR, MIR	2005 to 2006	60 km×60 km	14+5
FORMOSAT-2		8 m	B, G, R, NIR	2007	24 km×24 km	30
LANDSAT	MSS TM ETM	57 m 28.5 m 28.5 m/ 30 m	G, R, NIR B, G, R, NIR MIR B, G, R, NIR, MIR	1975 1986 and 1987 1999 to 2002	70 km×180 km	3 2 5
Terra	MODIS	250 m	R, NIR	2000 to 2008	1200 km×1200 km	366
CORONA	KH-4A	2.79 m	PAN	1965 and 1966	17 km×230 km	8
Aerial photographs		1.06 m	PAN	1954 and 1996	10 km×10 km	2

Table 2. Definitions of indexes, based on reflectance values in specific wavelengths. NIR stands for near infrared, MIR for middle infra-red.

Normalized Difference Vegetation Index	Normalized Difference Turbidity Index	Normalized Difference Pond Index
$\mathrm{NDVI} = \dfrac{\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{nir}} + \rho_{\mathrm{red}}}$ (2)	$\mathrm{NDTI} = \dfrac{\rho_{\mathrm{red}} - \rho_{\mathrm{green}}}{\rho_{\mathrm{red}} + \rho_{\mathrm{green}}}$ (3)	$\mathrm{NDPI} = \dfrac{\rho_{\mathrm{mir}} - \rho_{\mathrm{green}}}{\rho_{\mathrm{mir}} + \rho_{\mathrm{green}}}$ (4)

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Table 3. Confusion matrix and accuracy estimators for the classification of a whole LANDSAT-ETM image with a maximum likelihood classifier (image collected on 29 October 1999).

Overall accuracy: 97.16 %				
Kappa coefficient: 0.94				
Class label	Commission (%)	Omission (%)	Producer Accuracy (%)	User accuracy (%)
Blue ponds	0.00	3.99	96.01	100.00
Red ponds	0.00	1.76	98.24	100.00

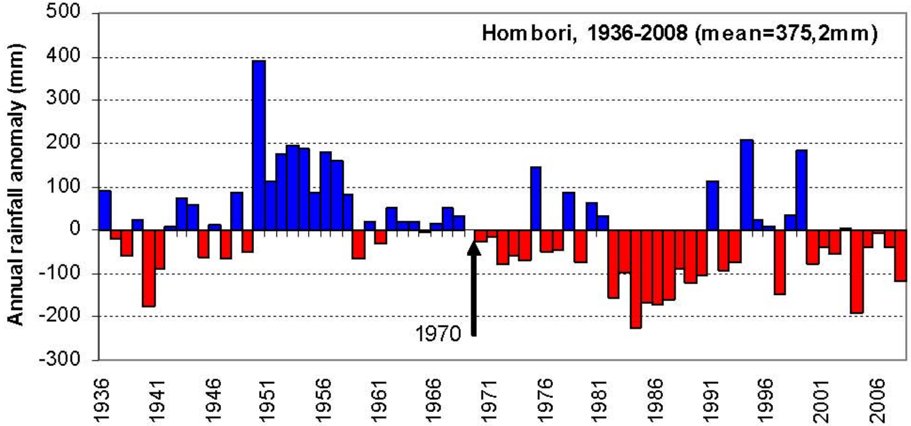

Fig. 1. Deviation of annual rainfall from the 1936–2008 average in Hombori (Mali).

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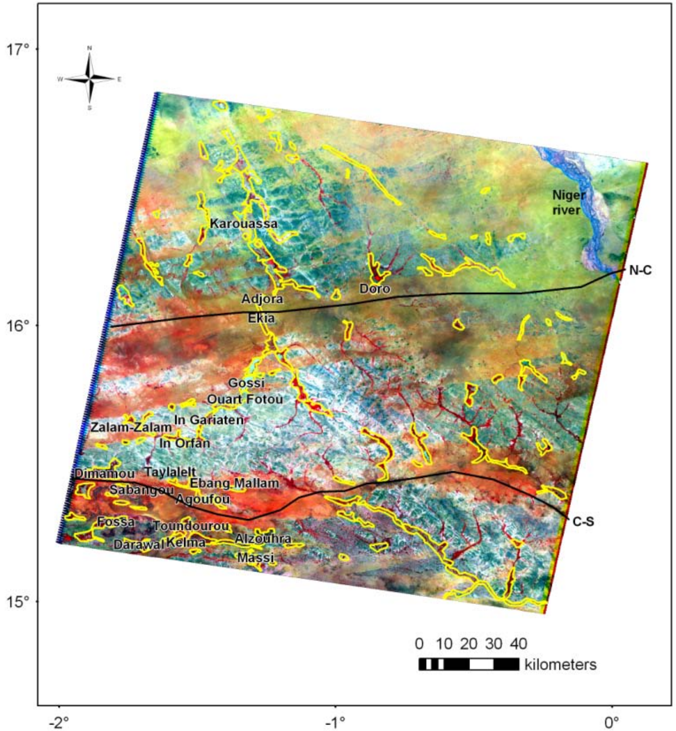

Fig. 2. LANDSAT ETM scene of the Gourma, with contours (yellow) delimiting areas where ponds are found (ponds are actually smaller than these contours). The scene is subdivided into three regions (separated by the C-S and N-C black lines), where ponds show different evolution with time (see text). Only the ponds explicitly mentioned in the text are labelled.

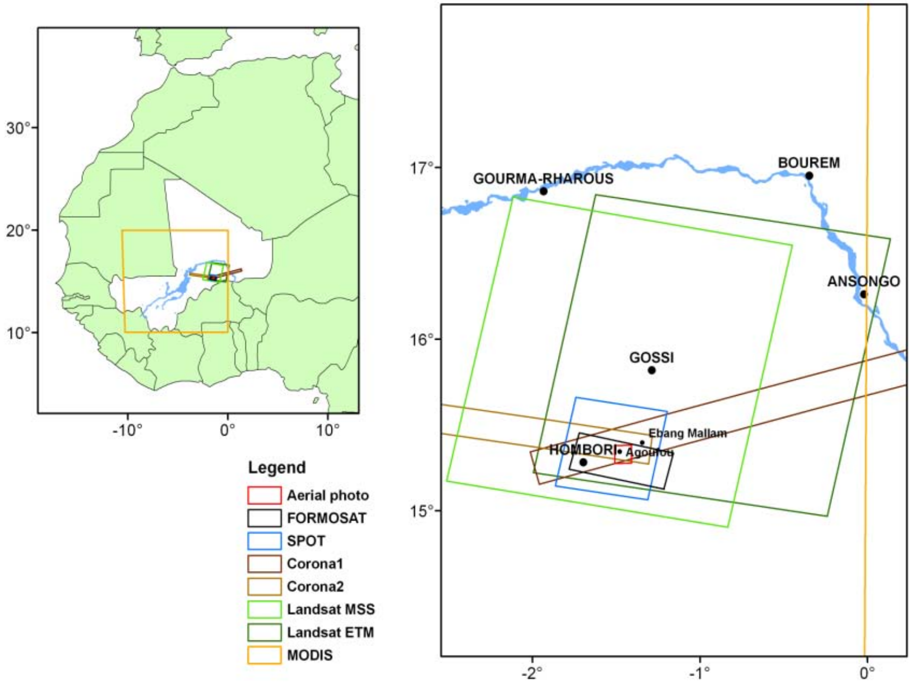

Fig. 3. Study site and frames of the different satellite and aerial images used to monitor ponds in the Gourma (Mali).

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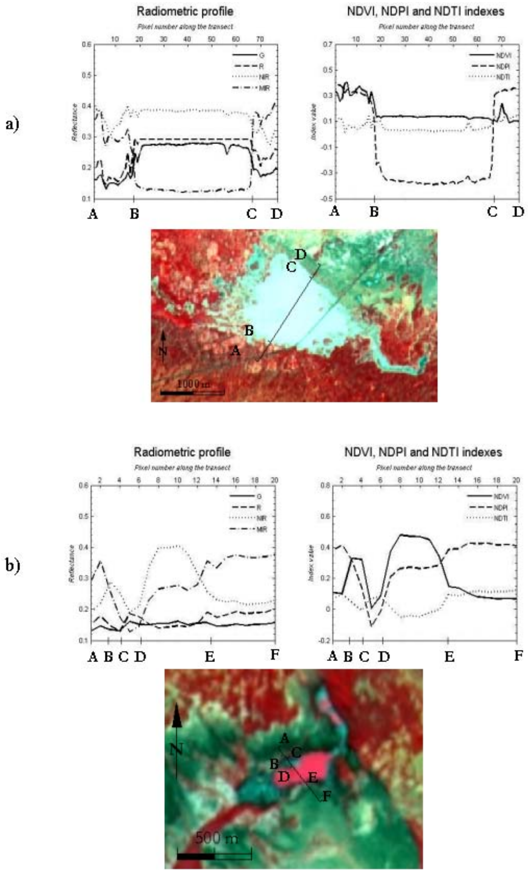

Fig. 4. Radiometric transects and corresponding indexes values for the two categories of ponds, based on a SPOT-4 image from the 22 August 2005. **(a)** Agoufou, "blue" pond, very turbid, without vegetation. A-B=vegetation on sand, B-C=open water, C-D=rocky outcrop. The broken line crossing the image (SW to NE) corresponds to the road connecting Hombori to Gossi. **(b)** Massi, "red" pond slightly turbid, very rich in vegetation. A-B=rocky outcrop, B-C=vegetation, C-D=free water, D-E=water covered with aquatic vegetation, E-F=rocky outcrop. Only the centre of the pond is covered with vegetation.

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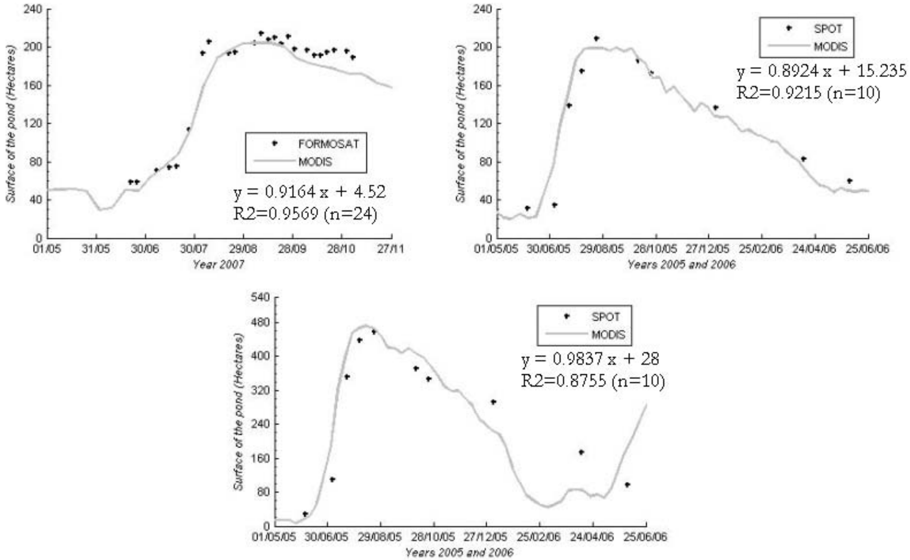

Fig. 5. Comparison of ponds' area derived from MODIS with area derived from SPOT-HRVIR and FORMOSAT-2. Top is Agoufou, bottom is Ebang Mallam.

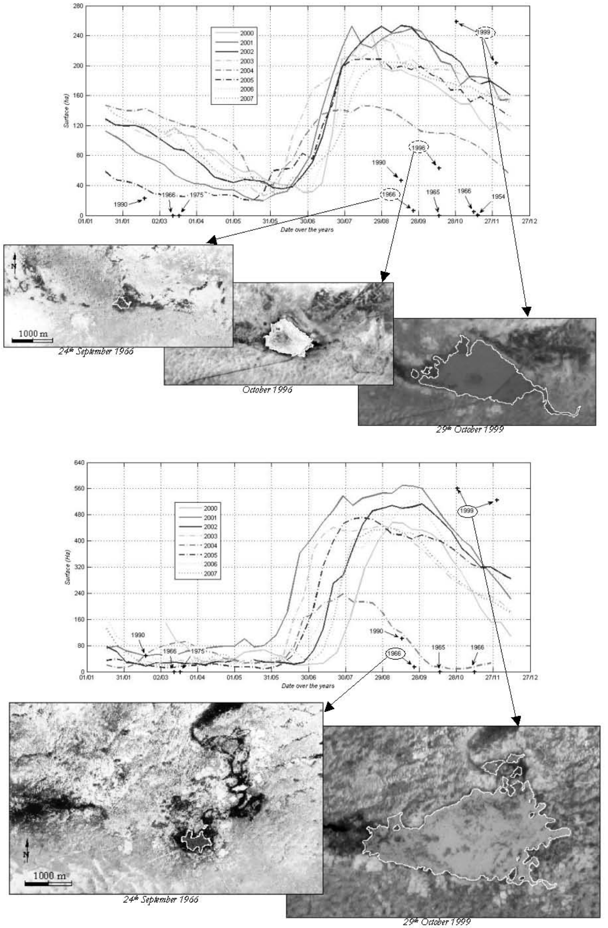

Fig. 6. Variation of the surface of Agoufou (up) and Ebang Mallam (down) over the last 50 years showing a dramatic increase. Curves are derived from MODIS data, while isolated dates come from LANDSAT, SPOT or panchromatic images. The scale is uniform throughout all images.

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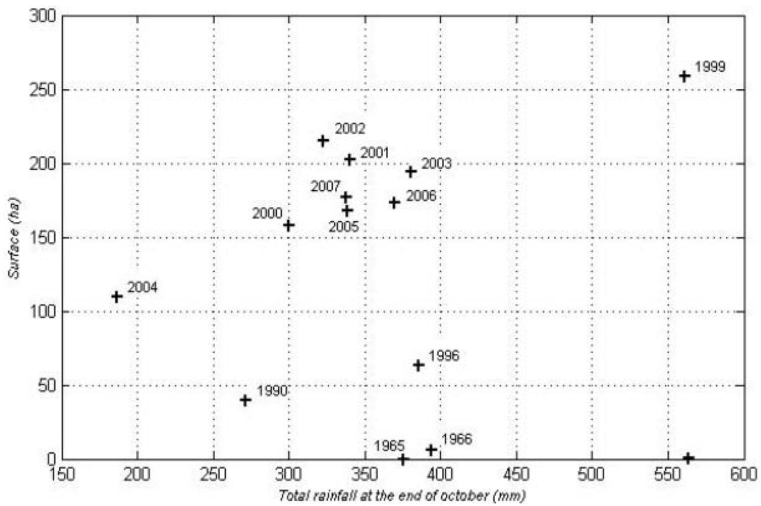

Fig. 7. Pond's area versus annual precipitations for the pond of Agoufou, showing a change in pond regime starting in the early 90'.

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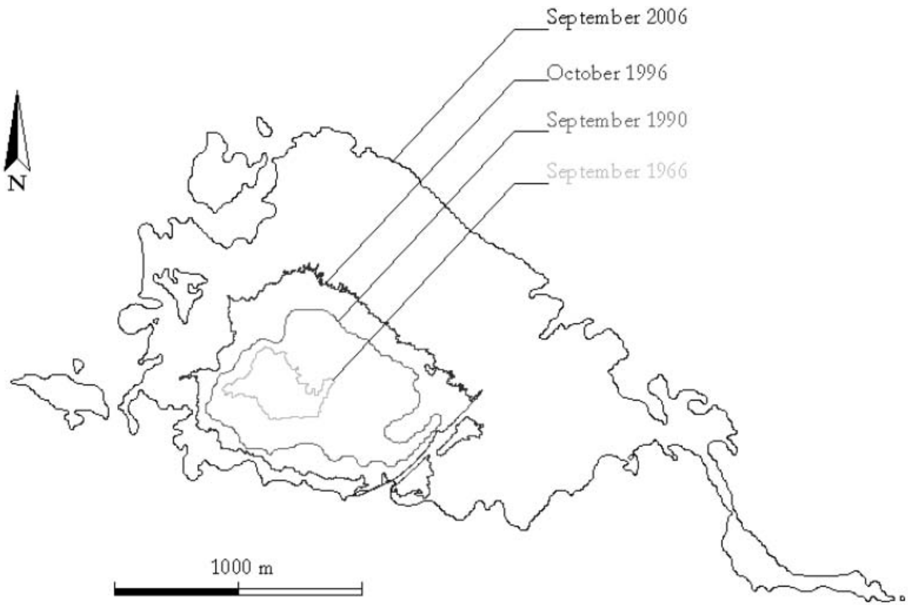

Fig. 8. Successive contours of the pond of Agoufou, between 1966 and 2006, at the end of the rainy season, showing the remarkable increase of the pond.

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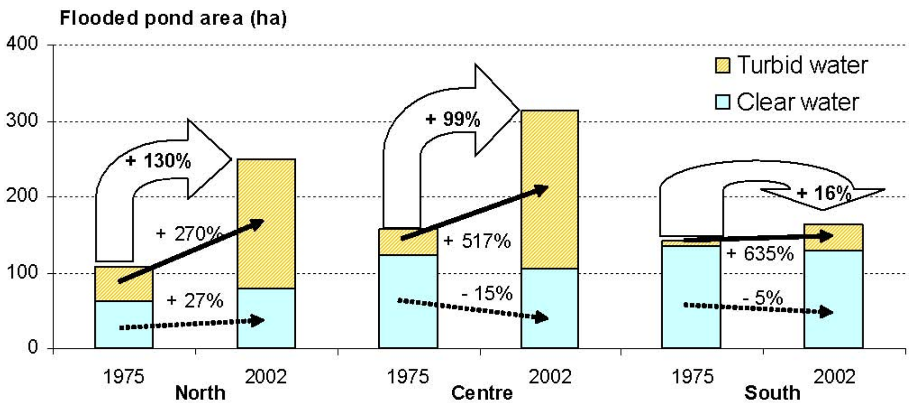

Fig. 9. Change in mean areas flooded with clear or turbid water in ponds (92 in total) observed between 14/09/1975 and the 03/09/2002 in central Gourma. Mean relative rates of change are calculated for the overall flood and for both clear and turbid water. Ponds are grouped following their location in the Gourma (see map in Fig. 2).