Flood monitoring of the Inner Niger Delta using high resolution radar and optical imagery

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Abstract This paper describes the monitoring of flooding in the Inner Niger Delta (Mali) from September 2008 to April 2010 using high resolution radar (C-band quad-polarization from Radarsat-2) and optical imagery (SPOT 4 and 5). Treatments, based on statistical parameters calculated using co-occurrence matrices, supervised classifications and three field surveys, were used to classify the images in three categories: open water, flooded vegetation and unflooded land. The overall accuracy evaluated by confusion matrices varies from 81% to 96%. The flooded areas, ranging from 3% to 65% of the surface studied, confirm the significant impact of annual flooding in the region. Radar images can identify soil properties even when remotely-sensed objects are characterized by dense, herbaceous vegetation and are also effective when cloud cover is thick.

Key words Radarsat-2; SPOT; Inner Niger Delta; flood monitoring; Mali

INTRODUCTION

Wetlands are the richest and most diverse ecosystems in the world. They control flooding, prevent drought, improve water quality, maintain water resources, temper erosion and serve as leisure areas (Novitzki *et al.*, 1996). Tropical areas, where a large proportion of food resources are linked to aquatic environments, are very dependent on the sustainability of these ecosystems. In 2007, the Intergovernmental Panel on Climate Change (IPCC) published an alarming report on the consequences of global warming (IPCC, 2007): by 2080, nearly 3.2 billion people will probably suffer from severe water shortages and 600 million from hunger as a result of droughts.

Africa is among the continents most concerned by the impact of climatic fluctuations on water resources. Indeed, the region has been subjected to environmental and particularly climate changes since the 1970s (L'Hôte *et al.*, 2002; Andersen *et al.*, 2005). More than two-thirds of the continent is between the tropics and the major droughts that hit the Sahel in the 1970s had dramatic, lasting consequences for the population. Lake Chad is a spectacular example of the effects of changing climatic conditions in tropical Africa. Its area was more than 22 000 km^2 in the 1960s, but it now consists of several non-perennial lakes covering less than 2000 km^2, with serious ecological consequences for the region and for the subsistence of local populations (Lemoalle *et al.*, 2008). The Inner Niger Delta (IND) is the largest flood zone in Mali has faced a similar problem of the sustainability of water resources since the 1970s as the flood zone area has decreased by 60% (Orange *et al.*, 2002; Mariko, 2003). Integrated management of these resources with a view to improving the standard of living of populations and conserving ecosystems, requires knowledge of flood dynamics.

This study proposes a method for monitoring flood dynamics in the IND. Given the scale of the area concerned, the use of satellite images is essential. Studies using optical imagery have already been conducted to trace the evolution of flooded areas in the Inner Niger Delta using the infrared channel of Landsat images for the 1973/1974 hydrological season (Blanck, 1993). Since then, Batti (2001) and Mariko (2003) showed the interest of NOAA-AVHRR images for observing the flooded areas. These images made it possible to work on the scale of the delta and to model the functioning of its hydrosystem. However, all these authors were hindered by cloud cover that prevented regular monitoring at times throughout the year. The vegetation was also a serious hindrance for the plotting of flooded areas (see e.g. Bied-Charreton *et al.*, 1978). In this context, synthetic aperture radar (SAR) constitutes an alternative solution as it can operate "in all weather" and is sensitive to flooded areas, even when vegetation is present (Henderson & Lewis, 2008). The launching of new very high resolution Radarsat-2 sensors in 2007 generated new ambitions for furthering knowledge about these zones, but studies on the quality of the information are required.

STUDY AREA

The source of the Niger is in the Fouta Djalon mountains in Guinea; the river then flows northeast, crossing the Sahel zone. It subsequently runs southeast to the Gulf of Guinea after flowing for 4200 km. When it crosses Mali, the Niger feeds a huge quantity of water into the IND, one of the most remarkable hydrographic systems in West Africa (Fig. 1). Located in the Sahel zone and covering some 40 000 km^2, it stretches from Ké-Macina to Timbuktu. The upstream delta (as far as Lake Debo) consists of a set of plains and basins regularly inundated by the floods of the Niger and its tributary the Bani. The downstream delta from Lake Debo to Timbuktu is a very diffuse hydrosystem in a dune/interdune system that limits the flooded areas. The IND slows the annual river flood by about 1–3 months (Batti, 2001) and evaporates about 40% of the flow of the Niger (Mariko, 2003).

A great number of socio-economic issues are related to the size and flood dynamics in the delta, where fishing, farming and grazing alternate according to the annual flooding regime. The IND has a population of over a million people, and crops (rice and sorghum), fisheries (>80% of Malian production) and animal farming are essential to the national economy.

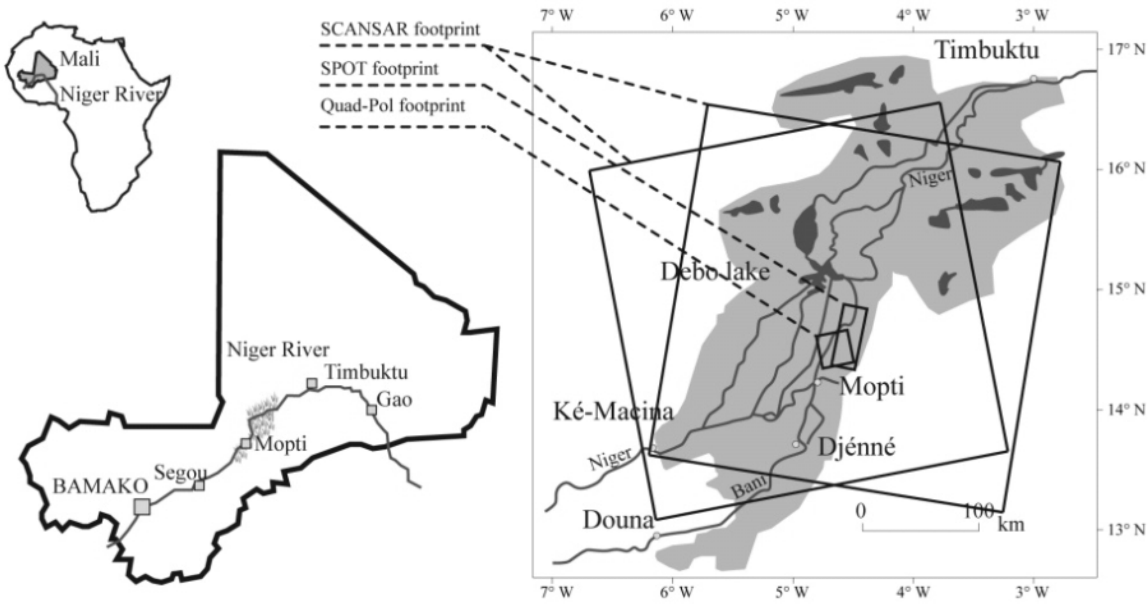

Fig. 1 Location of the Inner Niger Delta in Mali and position of satellite image footprints.

MATERIALS AND METHODS

Satellite images

Ten images from different sensors were acquired for the study (Table 1). Radarsat-2 images were acquired by the SOAR programme (Science and Operational Applications Research for RADARSAT-2) and SPOT images were obtained thanks to the ISIS (*Incitation à l'utilisation Scientifique des Images SPOT*) CNES (*Centre National d'Etudes Spatiales*) programme.

Ground surveys

Ground surveys were used to collect approximately 150 located, described and photographed points during three missions conducted during different hydrological seasons in November 2008, May 2009 and March 2010. Quad-Pol images obtained shortly before each mission were used to locate the reference sites during the survey operations. Each image was first segmented in 16 classes using Whishart's unsupervised polarimetric classification (Lee *et al.*, 1999). All the classes were examined and documented. The field missions were conducted while other Quad-Pol images were being recorded.

Table 1 Satellite images used in the study.

Sensor	Spectral band	Canal	Spatial resolution	Acquisition date	Source	Spatial coverage
Radarsat-2 Quad-Pol	HH HV VH VV	C Band 5.5 cm	11 m	11/11/2008 08/04/2009 02/05/2009 10/11/2009 28/12/2009 14/02/2010 10/03/2010 27/04/2010	SOAR	50 × 50 km
SPOT 4	Green –Red –PIR	0.50 – 0.89 µm	20 m	24/04/2009	SPOT image CNES (ISIS)	
SPOT 5	Green –Red– PIR – MIR	0.50 – 1.75 µm	10 m	2/11/2008	SPOT image CNES (ISIS)	60 × 60 km

Classification methods

Radarsat-2 Quad-Pol images The Radarsat-2 Quad-Pol images were processed using the *ESA PolsarPro* program and *ENVI* software using a method synthesised in Fig. 2. The difference in back scattering between the four polarisation methods (HH, HV, VH, VV) of Radarsat-2 is fairly strongly marked (Fig. 2) and varies according to the season. Assessing the flooding dynamics in the IND requires the identification of three types of surface: open water, unflooded land and flooded vegetation. If wind effects are not taken into account, open water is a smooth surface and identified by C-band specular reflection. Its colour is very dark in the image. Unflooded land also has rather dark colours. In contrast, flooded vegetation features strong back scattering and pale colours. The *PolsarPro* program was used to calculate a covariance matrix to provide a complete description of the scatter properties of the target by creating seven derived images (Cloude & Potier, 1996). Processing described by Frost (1982) was then applied to reduce *speckle*, which is an inherent noise in a radar signal that affects radiometric quality (Polidori, 1996). Photo interpretation of the seven images was performed to select those most suitable for the classification of flooded zones according to the season. The images were georeferenced and the training plots surveyed during the field missions were divided into three categories: open water, flooded vegetation and unflooded land. The histograms of these theme plots made it possible to perform the natural setting of thresholds to reduce image dynamics to three classes. Dry season brilliances were very readily differentiated in a single polarisation. Several bands were necessary to reduce high water period images to three classes. The coloured composition was used as a medium for a supervised Mahalanobis classification (1936). Finally, a median filter was applied to smooth the classifications.

HRV SPOT images Prior geometric adjustment was required to work on a 14 km wide strip common to both images. The resampling of the SPOT5 image at the resolution of the SPOT4 image was then performed to homogenise the signal between the images and facilitate comparisons. Identification of open water, flooded vegetation and unflooded land was based on calculation of the normalised difference vegetation index (NDVI) (Rouse *et al.*, 1973). This index measures chlorophyll activity in the plant cover, even when this is flooded. It is also a good indicator for identifying open water. Each SPOT multispectral image was also reduced to three composite bands representing the first three components of a principal component analysis (PCA,

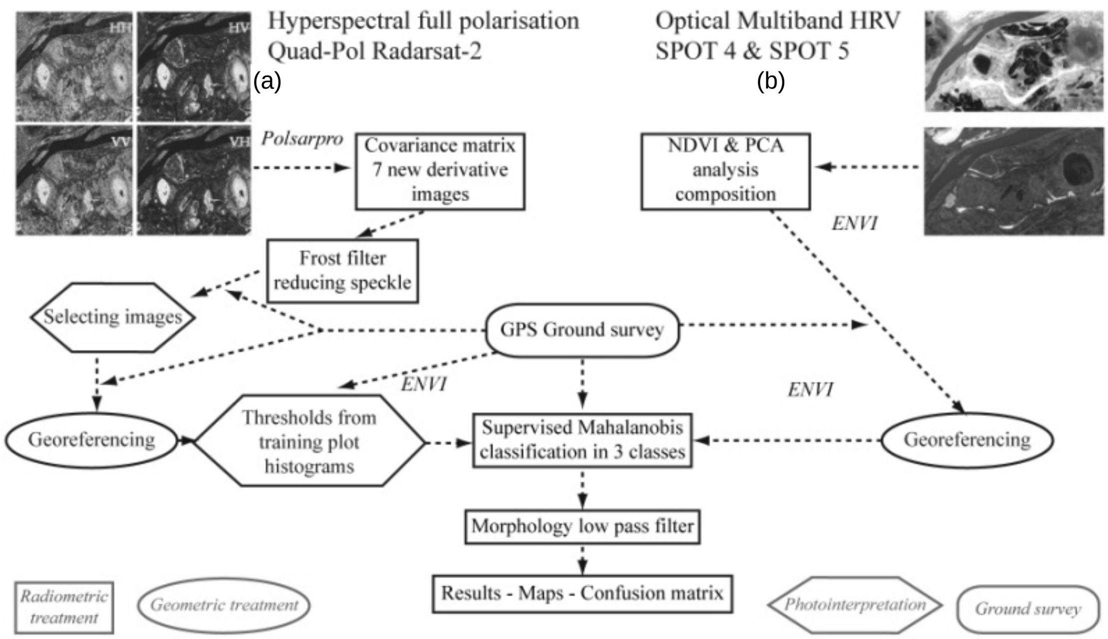

Fig. 2 Treatment methodology: Radarsat-2 Quad-Pol (a) and HRV SPOT (b) images.

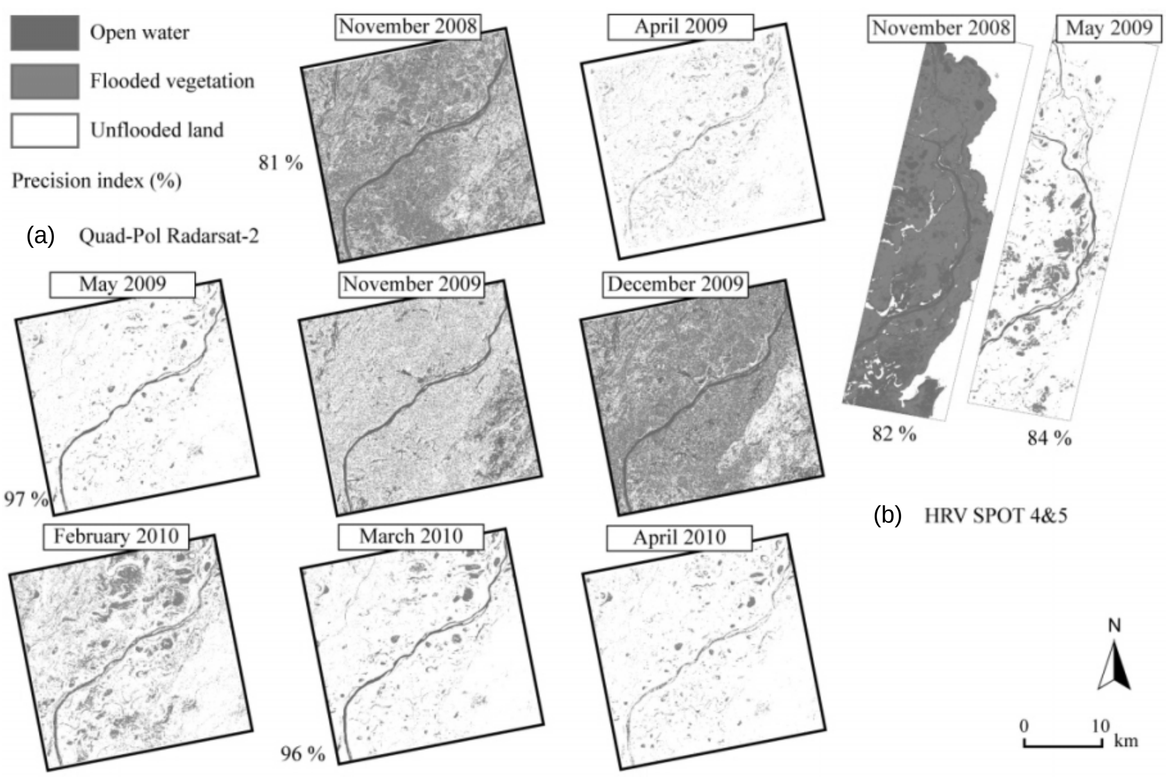

Fig. 3 Monitoring of flooding of the IND from 2008 to 2010 by the classification of (a) Quad-Pol Radarsat-2 images and (b) HRV SPOT 4&5 images.

see e.g. Fung & Ledrew, 1987; Millward *et al.*, 2006). The NDVI for each SPOT image was finally associated with these neochannels using a technique proposed by Ruelland *et al.* (2011).

Plots resulting from the references collected in November 2008 and May 2009 were used for training for a supervised Mahalanobis classification (1936) of the NDVI-PCA combination on the two dates studied. Finally, a median filter treatment was applied to the classifications.

Field data integration and validation The training plots for the date of the images concerned were divided into two samples for processing the Radarsat-2 Quad-Pol images and the SPOT HRV images. One sample was used for classifications and the other for the validation of the results by calculation of confusion matrixes and an index of overall precision.

RESULTS

Overall precision of the classifications of the Quad-Pol images is 81%, 97% and 96%, respectively, for the periods November 2008, May 2009 and March 2010. These results show the quality of the classifications (Fig. 3(a)).

The temporal dynamics of the flood is characterised by a high water period in November 2008, November 2009 and December 2009 and a low water period from February 2010 to April 2010. The classifications are a good reflection of the hydrological regime of the IND. During high water periods, the zone is practically covered by dense flooded vegetation and marshland to which access is difficult. In the dry season, the river flows in its bed and a host of ponds with plants and small channels form a loose mass of water. Open water and flooded vegetation are shown to represent respectively 43% and 22% of the study area in November 2008. The trend is reversed in April and May 2009, with 2.5% open water, 4% flooded vegetation and more than 90% unflooded land. The 2009–2010 hydrological season was monitored in more detail. The flood peaked at the end of December. The proportion of open water was distinctly smaller than it had been in November 2008, but the flooded vegetation was denser. In December, 24% of the area of the image consisted of open water. The fall in the water level took place from January to April with a decrease in the areas of flooded vegetation and open water to low points of 0.3% open water and 3.7% flooded vegetation in April 2010.

The SPOT images were used to monitor flooding of the IND on two dates (Fig. 3(b)): during the flood period (November 2008) and during the dry period (May 2009). The overall precision indexes are 82 and 84%, respectively, for the treatment of these two images. Nearly 50% of the area consisted of flooded vegetation in November 2008 while flooded vegetation plus open water did not exceed 20% in May 2009.

Table 2 Comparison of classifications from Quad-Pol (Radarsat-2) and HRV (SPOT) images.

	November 2008		May 2009	
	Quad-Pol	HRV	Quad-Pol	HRV
Open water (%)	43.6	32.4	2.4	3.2
Flooded vegetation (%)	21.9	49.1	4.4	16.6
Unflooded land (%)	34.5	18.5	93.1	80.2

The flooded areas drawn from the classifications of Quad-Pol and SPOT images were compared (Table 2) in their common coverage on the two common dates. The scales of size are coherent overall, with the differences being greatest for November 2008. The area of flooded vegetation in the SPOT image classification is more than 20% greater than that in the radar image. Conversely, the areas of open water are overestimated in the Quad-Pol classification. As radar is sensitive to ground roughness characteristics and most of the area unflooded in November consists of bare indurated clayey-silty soils, there is confusion between unflooded land and open water. In contrast, confusion between unflooded vegetation and flooded vegetation occurs with the optical sensor. However, this can be used to distinguish between bare soil and soil with plant cover. A radar signal with a 5.5 cm wavelength is better able to penetrate vegetation than the SPOT-HRV images. This makes it possible to better discriminate flooded vegetation areas from unflooded ones. In May 2009, the areas of open water were equivalent. The area of flooded vegetation indicated by the SPOT image is 12% greater than that of the radar image and, conversely, the area of unflooded land is 13% greater in the radar image.

DISCUSSION AND CONCLUSION

The dynamics of the IND flood characterised here are in agreement with that shown in precedent works (Batti, 2001; Mariko, 2003). The flooded area is 65% greater during the winter period (November–December) while less than 3% of the zone is under water in the dry period (May). These results confirm the considerable impact of the flood on the variation of landscapes in the region and consequently on the remote sensing images studied. The three field missions performed within the framework of the project have been sources of substantial knowledge aimed at ensuring the quality of processing operations. They improved georeferencing, provided training and validation plots and enabled a sensitive approach to the field that is essential for processing.

Radarsat-2 images had never been used to monitor flooding in this zone. It made it possible to overcome meteorological constraints related to dust-bearing mist in the dry season and clouds during the rainy season. The hyperfrequencies reputed to be effective in identifying soil moisture made good results possible for the dry season, especially by means of the precise identification of ponds and islands. With regard to flooded vegetation, radar signals are fully suited to the characterisation of humid zones, as had previously been shown by Henderson & Lewis (2008). Radar imaging has proved its ability to identify flooded vegetation in both the rainy and dry seasons and thus forms a good alternative to optical imaging in this environment.

However, radar also has limits. Surface roughness strongly influences the back scattering of the signal. Waves form on the surface of the Niger when the Harmattan blows in the delta, and modify the specular reflection of the water. Many zones feature indurated bare soil whose roughness is similar to that of a water surface. Optical images also display bias: the angle of incidence, shadows, sun angle, clouds, sandstorms and vegetation on flooded land affect image and classification quality.

The interest of diachronic, multi-source analysis of the flooding of the IND has thus been shown. Two aspects of the complementarity of radar and optical imaging for thematic cartography can be considered. From an operational point of view, the "all weather" feature of radar fills gaps in zones previously plotted using optical images. From a purely thematic point of view, flooded vegetation and bare ground are seen in a very different way by the two types of sensor and this significantly increases the possibility of distinguishing between the two by comparing images. To conclude, radar imaging complements optical imaging within the framework of the monitoring of flooding of the IND.

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