Satellite monitoring of Yaere flood plain dynamics (north Cameroon)

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Abstract The Yaere flood plain in north Cameroon is subject to annual flooding caused by local rainfall and Logone River overflow. Large evaporative loss (12 km^3 year^{-1}) from this 8000 km^2-flooded area causes a significant loss in water supply to Lake Chad. Flood monitoring is performed using the 10-daily 1 km spatial resolution small water body (SWB) product generated by the Joint Research Centre (JRC) of the European Commission, as a result of processing SPOT VEGETATION images. As this method was initially designed for the detection of small water bodies in arid and semi-arid regions, a field validation showed the benefits and drawbacks for the monitoring of large flood plains. Difficulties in reconstructing the surfaces of large open water bodies were observed, while a good ability for reproducing water spreading and irrigation conditions over the rice-growing areas was proven. Observed water levels at the outlet of the plain were fully consistent with remotely monitored flood spreading across the whole plain that occurs when the maximum discharge of the Logone River is greater than 1500 m^3 s^{-1}. Annual SWB composite maps coupled with DEM information were found to provide consistent information on the water path across the plain.

Key words Yaere; flood monitoring; remote sensing; field validation; Small Water Bodies; flow path; DEM; SRTM

INTRODUCTION

The hydrologically active part of the Lake Chad Basin (LCB), with an area of 800 000 km^2, has several flood plains (Komadougou Yobe, Salamah Messanya, Yaere), which play an important role in the water balance of Lake Chad. Indeed, the evaporated volume in these wetlands is about 28 km^3 year^{-1}, while the volume provided by the Chari River is 38 km^3 year^{-1} (Gac, 1980). Moreover, flooding of these areas allows the various human communities to carry out their fishing and farming activities during the rainy season. These areas are also important for wildlife preservation. Located in the Yaere plain (north Cameroon) the Waza National Park has a large wildlife population, including gazelles, lions, elephants and giraffes (Loth, 2004).

Among the various wetlands of the LCB, the Yaere in northern Cameroon is particularly important. On the one hand, the evaporated volume from the flood plain is about 12 km^3 year^{-1} (Naah, 1990), i.e. a significant proportion (40%) of the total amount evaporated in the LCB. On the other hand, this hydrological system has been subjected to large changes in recent years. These changes have resulted from the combination of climatic factors such as the successive years of droughts in the 1970s and 1980s, and anthropogenic factors, among which the construction of the Maga dam in the southeast and the proliferation of fishing channels in the plain are the most important ones. The Waza-Logone project conducted by the International Union for Conservation of Nature (IUCN) (Loth, 2004) in the 1990s led to the acquisition of environmental information in this area where data availability remains low, apart from some past studies (Bouchardeau, 1967; Benech *et al.* 1982; Olivry, 1986; Naah, 1990). The availability of a remote sensing-derived time series of water body observations covering a sufficiently long period (Haas *et al.*, 2009) is a real opportunity to understand the dynamics of hydrological systems hardly accessible during the flood period.

STUDY AREA

Geography

The Yaere flood plain is located south of Lake Chad, between 10°N and 12°N (Fig. 1). The plain is bounded in the South by a 170 km-long sandy ridge, in the West by the Logone River and in the

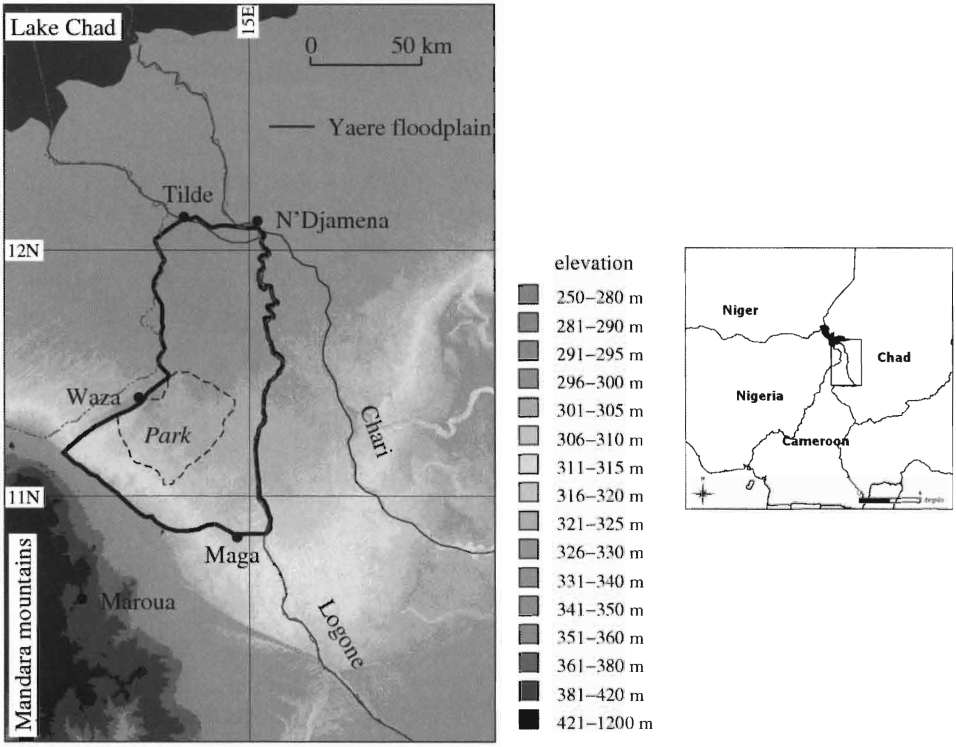

Fig. 1 Study area: the Yaere flood plain is located in the South of Lake Chad. Black line is the flood plain limit.

East by the Nigeria-Cameroon border. The natural outlet of the plain, El Beïd, marks the northern boundary. The plain, with an area of 10 000 km^2, is characterized by an extremely flat relief (Naah, 1990). Altimetric data show that the plain elevation varies from 287 m to 300 m from South to North, corresponding to a mean slope of 0.12 m km^{-1}.

Climatic context

The Yaere flood plain is located at the limit of the Sudanian climate in the South, and of the Sudano-Sahelian climate in the North (Naah, 1990). The rainfall is controlled by the Intertropical Convergence Zone (ICTZ) and is characterized by two distinct seasons:

(a) the rainy season, from May to September: the rise of ICTZ and the presence of moist air masses cause maximum precipitations in July and August;

(b) the dry season from October to April: after the descent of the ICTZ, continental high pressure is settled over the area. The hot air temperatures and dry harmattan wind then promote high evaporation of water in flooded areas.

Figure 2 shows the mean precipitation (P) and evaporation values (Ev) measured with evaporation tank, i.e. Class A Pan, over the period 1953–2002 for two towns located in extreme parts of the zone, Maroua in the South and N'Djamena in the North (Fig. 1). The P values were extracted from the CRUTS2.1 database of the Climatic Research Unit (CRU) (Mitchell & Jones, 2005).

Regarding P, seasonal variations are similar for the two stations, with maxima in August (206 mm $month^{-1}$ in N'Djamena and 243 mm $month^{-1}$ in Maroua). The difference between the annual totals of N'Djamena (597 mm) and Maroua (847 mm) is 250 mm, corresponding to a gradient of 125 mm by 100 km.

Evaporation is very high, with values between 158 to 313 mm month^{-1} in N'Djamena (1964–1973) (Olivry *et al.*, 1996), and 179–420 mm month^{-1} in Maroua (1983–1987) (Naah, 1990). The maxima are observed during the dry season and the minima during the rainy season. Evaporation in Maroua is greater than in N'Djamena, with yearly totals of 3594 and 2824 mm year^{-1}, respectively. However, a direct comparison between these two stations must be carried out with caution. Firstly, the observation periods are of different duration. Secondly, the period observed for Maroua corresponds to a dry period, while the one of N'Djamena is prior to the 1973–1974 drought. According to Naah (1990), the mean annual evaporation in Yaere is about 3000 mm year^{-1}.

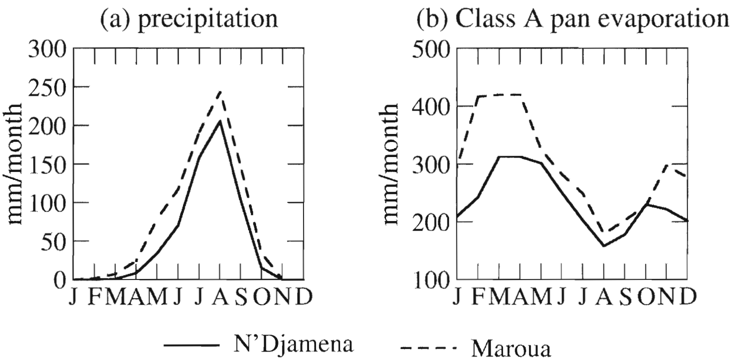

Fig. 2 Average monthly climatology for the N'Djamena and Maroua stations: (a) precipitation; (b) evaporation. Precipitation data were extracted and averaged from the CRUTS2.1 database (1953–2002). Evaporation data come from Class A pan measurements in N'Djamena (1936–1973) and Maroua (1984–1987).

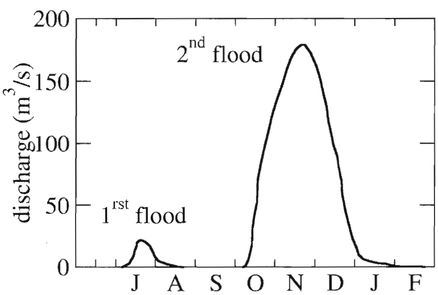

Fig. 3 El Beïd dual flood at the Tildé station (from Olivry, 1986). The first flood is mainly due to the local rainfall and small rivers while the second flood is the consequence of the Logone overflow and the water propagation across the plain.

Hydrology of the Yaere flood plain

Each year, Yaere is flooded by a process described by Bouchardeau *et al.* (1967), Benech *et al.* (1982), Olivry (1986) and Naah (1990). At the beginning of the rainy season, rainfall and flooding of mayos (local rivers) fill the pools that form with the first floods in the lowlands. In a second phase that starts in September, the flooding of the Logone River enters the plain via the Logomatia, a western parallel tributary of the Logone River; this flow being facilitated by many fishing channels dug through the embankment. This overflowing creates a water layer covering a part of the plain during three to four months. During this period, a water fraction goes back to the atmosphere via evaporation. If the water volume is large enough, i.e. when the flood discharge of the Logone River is greater than 1500 $m^3 s^{-1}$ at Bongor (Benech *et al.*, 1982), the remaining water reaches Lake Chad through the main outlet of the El Beïd plain at Tildé. This process is illustrated in Fig. 3, which shows the double flooding of El Beïd at Tildé station. During the flood recession, water returns to the Logone through the fishing channels and the Logomatia. The interannual water balance of the Yaere flood plain, as estimated by Naah (1990), is presented in Table 1. The evaporated volume of 12.3 km^3 $year^{-1}$ represents 44% of the total of 28 km^3 $year^{-1}$ evaporated at the entire LCB, as estimated by Gac (1980). These values show the importance of the Yaere flooding in the overall water balance of Lake Chad. The above-mentioned volumes correspond to averages prior to 1980.

Table 1 Interannual water balance of Yaere flood plain (from Naah, 1990).

Water volume	Contribution (km^3 $year^{-1}$)	Losses (km^3 $year^{-1}$)
Mayos	0.7	–
Precipitation	6.8	–
Evaporation	–	12.3
Logone	5.3	–
El Beïd	–	0.5
Total	12.8	12.8

DATA AND METHODS

Hydrological and geomorphological data

Hydrological data employed in this study is the time series of Logone discharges from the SIEREM database (Boyer *et al.*, 2006). Elevation data were extracted from the Digital Elevation Model (DEM) SRTM3" (Rabus *et al.*, 2003) and modified to be consistent with the local elevation reference from Institut Géographique National (IGN).

Remote sensing data and processing

Information about Small Water Bodies (SWB) is derived from the SPOT VEGETATION (VGT) satellite sensor that provides daily global information of the Earth surface at 1-km spatial resolution (CNES, 1999). The SWB identification is based on SPOT VGT-S10 (10-day synthesis) Maximum Value Composites (MVC) that includes the least atmospherically contaminated signal received during the 10–day period, i.e. a dekad (CNES, 1999). The starting day of each dekad, a term designed for SPOT VGT products, is set to the 1st, 11th and 21st of each month. The dekadal MVCs clearly show water bodies and humid vegetation, yet simple image classification does not provide sufficient results, because the spectral signatures vary together with the ecological conditions of these surfaces. To overcome these limitations, Gond *et al.* (2004) developed a robust contextual algorithm, which takes into account local contrast and is described briefly hereafter. For a detailed description of the algorithm please refer to Gond *et al.* (2004).

Since surface water highly contrasts with the surroundings in arid and semi-arid regions, Gond *et al.* (2004) generated an index of local contrast with values ranging from 0 to 1, which determines the difference between the regional average (i.e. the mean value computed on a moving window of 45 × 45 pixels – about 2025 km^2) and the actual pixel value. Values of local contrast close to zero show surfaces that are typical for the region whereas values different from zero show anomalies, like water bodies or humid areas. With simple thresholds, these specific surfaces are selected in the image and the state of surface water is defined for each pixel depending on the threshold value (Gond *et al.*, 2004; Bartholomé & Combal, 2006). Detected pixels can belong to three categories: free water, humid area or a mixture of free water and humid area. Free water is defined as an open water surface in contrast to humid area, which describes waterlogged ground with a high amount of vegetation content, either floating or growing inside or on the fringe of the accumulated water. SWB map is produced each 10 days according to this method. The geometrical accuracy of the SPOT VGT data of less than 160 m co-location accuracy allows the construction of a reliable time series (Bartholomé, 2006). Due to the recurrent observation, the seasonality of each pixel, i.e. when replenishment started and when drying out was completed, can be determined (Bartholomé & Combal, 2006).

SPOT VGT SWB maps are available for each dekad for the African continent from January 1999 until November 2008 and are distributed in near-real time (Combal *et al.*, 2009). The reliability of the dekadal SWB maps was assessed with a time series analysis that led to a map of temporary small water bodies (TSWB) at 1-km spatial resolution. A regional scale validation between 17°W to 26°E and 8°N to 20°N in the arid, semi-arid and adjacent dry sub-humid climate zone of sub-Saharan western Africa showed the high quality of the mapping approach (Haas *et al.*, 2009). The TSWB map is a synthesis of 9 years of 10-daily SWB detections between January 1999 and September 2007 (315 dekads). Further analysis of the SWB time series provided additional information on the seasonal recurrence of water bodies and their hydrological function. A map derived from a continuous time series assures the inclusion of temporary features, a clear advantage in comparison to other datasets, which are based on several single date observations.

Method

The methodology for describing the flood propagation in Yaere is based on a two-step approach. Firstly, several ground surveys, including GPS acquisition, photos and discussions with local people were conducted during November and December 2008 to validate the SWB data on three different sites: paddy fields close to Lake Maga, Lake Maga itself and the flooded area of El Beïd. In a second step, annual composite SWB maps were compared to elevation data for assessing the conditions of the water propagation in the plain.

RESULTS AND DISCUSSION

Paddy fields of Lake Maga

The dam of Lake Maga was built in the 1980s to create a reserve of water (600 million m^3) for the irrigation of paddy fields. These are located in the north of the lake (Fig. 4) with a surface of

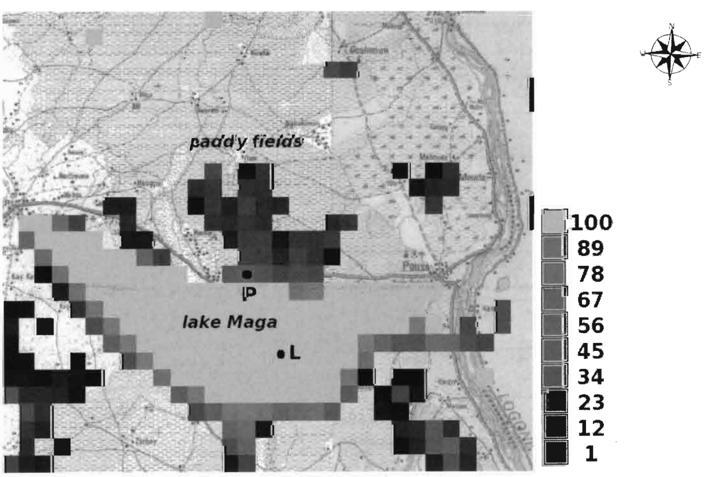

Fig. 4 TSWB map over Lake Maga and paddy fields. One pixel is 1 km × 1 km large. The grey scale represents the percentage of occurrence as free water in the SWB time series for each pixel. A value of 100 means that each time a signal was detected it corresponded to free water (basemap source: IGN).

6000 ha, among which 4500 ha are cultivated during the dry season and 1500 ha during the rainy season. Time series of SWB values for several paddy fields were extracted. Figure 5(a) shows this sequence for the point P where the dry season cropping clearly appears. Field impoundment begins at the end of January, followed by transplanting in February and March when the fields are fully inundated and a free water signal is detected. The growth of the rice until maturity in June and July corresponds to the humid area signal (water + vegetation) until the harvest period when the soil becomes dry and no more signal is detected with the SWB time series.

Lake Maga

SWB time series were extracted for a point in the centre of the lake (point L). As can be seen in Fig. 5(b), a problem occurs for detecting large free water surfaces. Rather than a continuous signal of "free water" as can be expected from the centre of a permanent lake, gaps occur in the signal. These gaps are observed in particular during the rainy season after June. Two hypotheses can explain this phenomenon: the first one is that the algorithm is efficient only for small surfaces since it works with local contrast. Large water surfaces strongly influence the regional average and thus are not detected with the contextual algorithm. Another explanation is linked to the timing of the observed gaps. They occur during the inflow of water that is heavily laden with sediment from the flooded mayos Boula and Tsanaga during the rainy season. The "chocolate"-coloured water does not contrast with the surroundings and thus is not detected as free surface water.

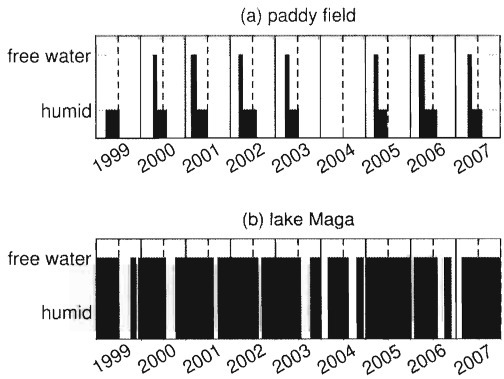

Fig. 5 Time series of two SWB pixels. Black area corresponds to the SWB values at two different pixels: (a) pixel located inside paddy fields (point P); (b) pixel located in the centre of Lake Maga (point L). Vertical solid lines (dashed lines) correspond to 1 January (1 June) of each year.

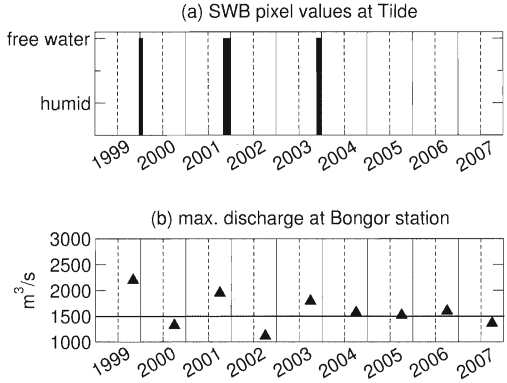

Fig. 6 (a) Time-series of SWB values at Tildé; (b) flood discharge of Logone River at Bongor station.

El Beïd River in Tildé

The flooded area of El Beïd at Tildé is a remarkable observation station since this outlet of the plain can be easily accessed with a road. The El Beïd road bridge narrows the outlet and thus amplifies upstream storage of water coming from the plain. The SWB images clearly show that this area was flooded in 1999, 2001 and 2003. This was confirmed *in situ* during discussions with the inhabitants of Tildé. The chronology of the SWB signal at the Tildé village (Fig. 1) is reported in Fig. 6(a) where the three above-mentioned years appear clearly. Moreover, the presence of water at Tildé is confirmed in Fig. 6(b) that shows the maximum flows of the Logone at Bongor station. In 1999, 2001 and 2003 the water flow exceeded the threshold of 1500 $m^3 s^{-1}$ defined by Benech *et al.* (1982), which allows water to cross the plain to Tildé.

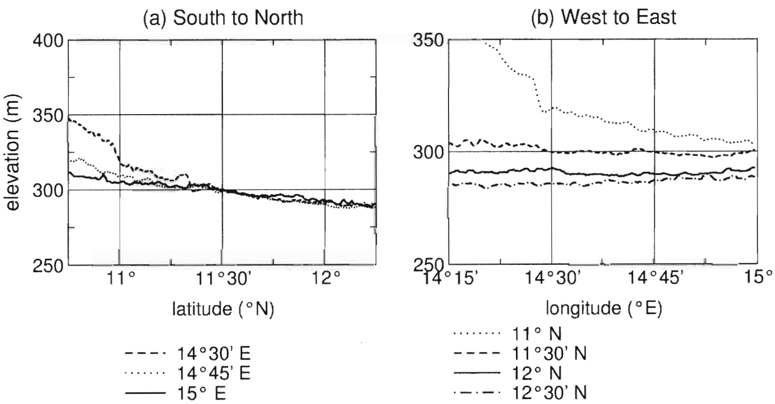

Fig. 7 Elevation profiles extracted from DEM SRTM3" over the Yaere flood plain, (a) latitude profiles; (b) longitude profiles. Elevation unit is metres above sea level.

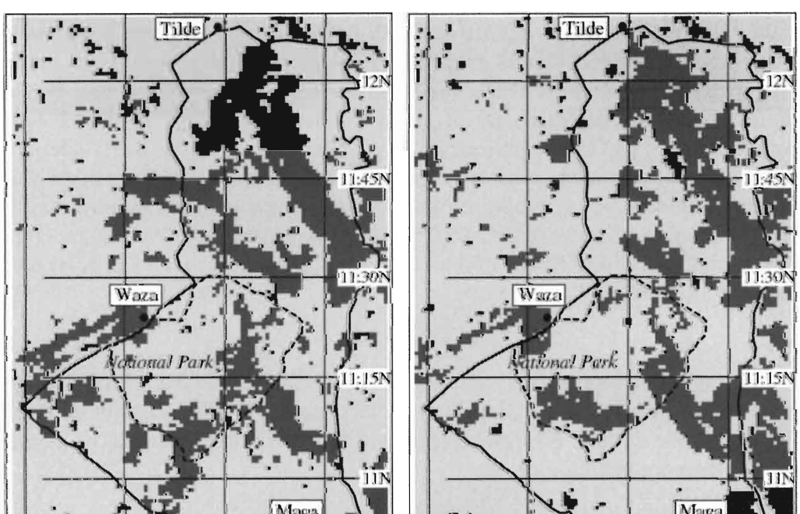

Fig. 8 Water in Yaere during floods of (a) 2000–2001; (b) 2003–2004. These maps are annual composite images of SWB data. Presence of water or water+vegetation at least during one 10–day period in the year is indicated by dark pixels.

Monitoring water propagation in the plain

Once the SWB images are validated, they can be used to monitor the water spread in the plain. As the relief of the plain is very flat, water does not propagate in a well-defined drainage network. Water either flows in fishing channels or accumulates in local ponds. The preferred paths of the water could be detected with the SWB images. In addition, flooded areas that were covered with herbaceous aquatic vegetation were detected as a mix of water and vegetation.

In a first step, DEM elevation profiles were extracted in North–South and West–East directions (Fig. 7(a),(b)). With regard to the profiles in latitude, the general trend is a slope from South to North of 0.16 m km^{-1}. By contrast, the East–West profiles do not show a uniform trend. In the South (11°N), the slope is oriented West to East. At 11°30'N, the overall slope is zero, with a depression between 14°45'E and15°E. The two northern profiles (12°N and 12°30'N) present an inversion of the slopes, both of them being oriented East to West.

This morphological description is fully consistent with the SWB images. Two SWB composite images show the presence of water over the periods 2000–2001 and 2003–2004 (Fig. 8(a),(b)). Close to 11°N, the flooding stays along the Logomatia. North of the Waza National Park, at 11°30'N water accumulates between 14°45'E and 15°E, which is consistent with the depression mentioned in the paragraph above. In the northern flood plain, the preferred path of the water towards Tildé is the North–West direction, which is consistent with the combination of North–South and East–West elevation gradients.

CONCLUSION

Some remote sensing studies were carried out over the Yaere flood plain (Naah, 1990; Loth, 2004). However, these works are based on high-resolution Landsat images acquired at specific moments of the year, generally during the high level water period. Therefore, they describe the situation of the flood at a given time. Remote sensing-derived time series of surface water detections allow the flood dynamics to be monitored continuously. This is key to assess the impact of climate change and anthropogenic effects on wetland dynamics. However, the SWB products have some limitations. The algorithm does not work well for large free surface water areas. Moreover, the spatial (1 km^2) and temporal (10–day) resolutions can be an obstacle for very local studies. On the other hand, the SWB data is produced in an operational manner at near-real time and no additional processing is needed. Once validated for an area, as in the case of Yaere, it provides information about the characteristics of artificial sites such as paddy fields, or natural areas. Concerning the detection of water presence and paths in the plain, the SWB data are fully consistent with topographic parameters such as depressions and slopes that determine the flood propagation. The next step will be to integrate MODIS time series (7-day temporal and 500 m spatial resolution) and compare them with the SWB products. This will improve the understanding of the potential and limitations of the SWB product and provide more accurate information on the dynamics of the Yaere flood plain.

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REFERENCES

Bartholomé, E. (2006) The VEGETATION mission. In: *VGT4Africa User Manual*, First edition (ed. by E. Bartholomé). Office for Official Publication of the European Communities, Luxembourg.

Bartholomé, E. & Combal, B. (2006) Small Water Bodies. In: *VGT4Africa User Manual*, First edition (ed. by E. Bartholomé). Office for Official Publication of the European Communities, Luxembourg.

Benech, V., Quensiere, J. & Vidy, G. (1982) Hydrologie et Physico-Chimie des eaux de la plaine d'inondation du Nord Cameroun. *Cah. ORSTOM, sér. Hydrol.* **XIX**(1), 15–35.

Bouchardeau, A. (1967) L'amortissement des crues du Logone en aval de Laï. *Cah. ORSTOM sér. Hydrol.* **IV**(4), 3–14.

Boyer, J. F., Dieulin, C., Rouche, N., Cres, A., Servat, E., Paturel, J. E. & Mahé, G. (2006) SIEREM an environmental information system for water resources. In: *Proc FRIEND Conference on Climate Variability and Change – Hydrological Impacts* (Havana, Cuba), 19–25. IAHS Publ. 308. IAHS Press, Wallingford, UK.

CNES (1999) General description of the system. The VEGETATION Web site, http://vegetation.cnes.fr/.

Combal, B., Haas, E. M., Andigué, J., Nonguierma, A. & Bartholomé, E. (2009) Operational monitoring of water bodies in arid and semiarid regions with SPOT-VEGETATION satellite: Contribution of Eumetcast and recent research projects. *Sécheresse* **20**(1), 48–56.

Gac, J. Y. (1980) Géochimie du bassin du lac Tchad. PhD Thesis, Travaux et Documents de l'ORSTOM, ORSTOM, Paris, France.

Gond, V., Bartholomé, E., Ouattara, F., Nonguierma, A. & Bado, l. (2004) Surveillance et cartographie des plans d'eau et des zones humides et inondables en régions arides avec l'instrument VEGETATION embarqué sur SPOT-4. *Int. J. Remote Sens.* **25**(5), 987–1004.

Haas, E. M., Bartholomé, E. & Combal, B. (2009) Time series analysis of optical remote sensing data for the mapping of temporary surface water bodies in sub-Saharan western Africa. *J. Hydrol.* **370**(1–4), 52–63.

Loth, P. (2004) *The Return of the Water: Restoring the Waza Logone Flood Plain in Cameroon.* IUCN, Gland, Switzerland and Cambridge, UK.

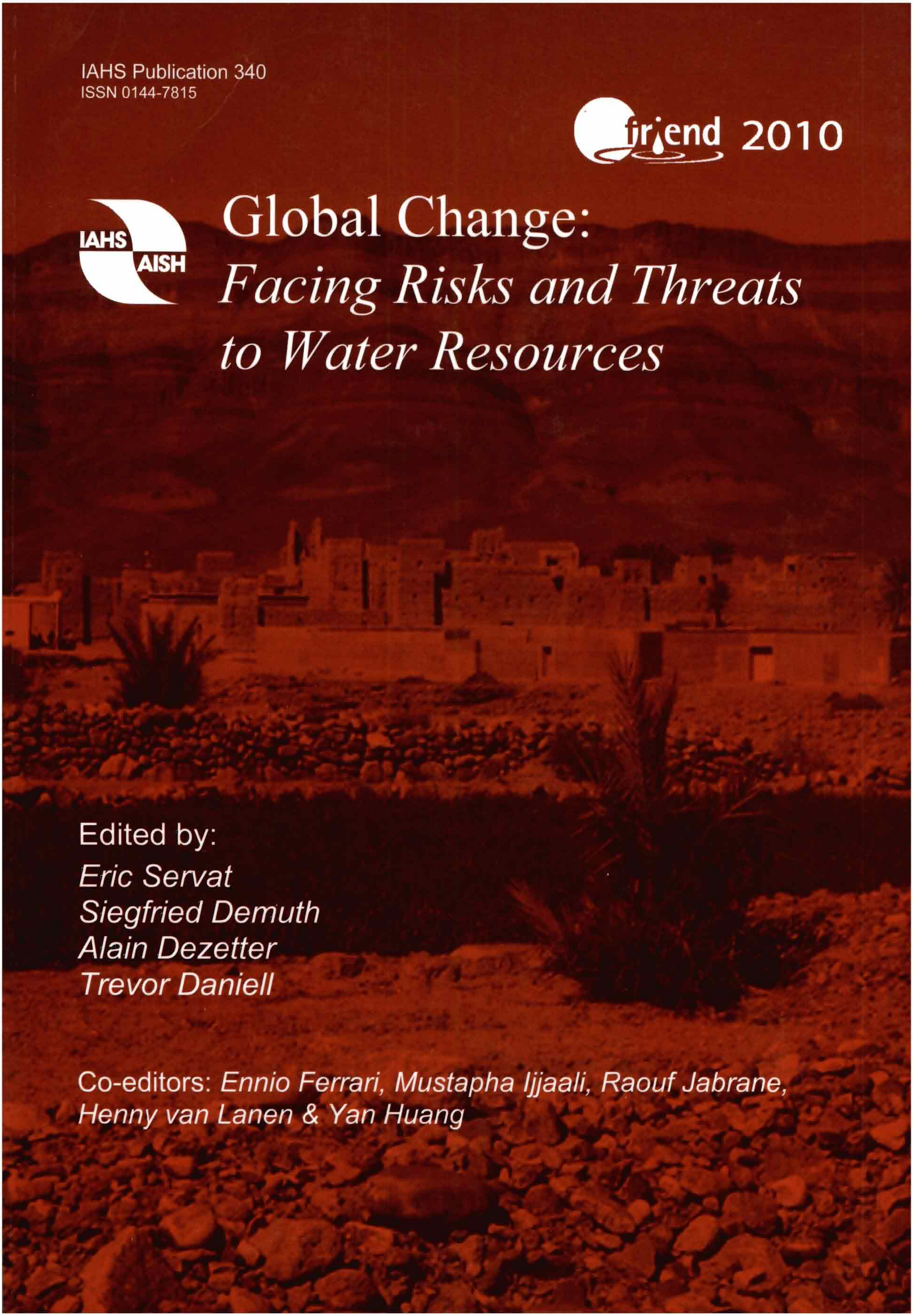
Mitchell, T. D. & Jones, P. D. (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol* **25,** 693–712.

Naah, E. (1990) Hydrologie du grand Yaere du nord Cameroun. PhD Thesis, Yaoundé University, Yaoundé, Cameroon.

Olivry, J. C. (1986) *Fleuves et rivières du Cameroun.* Collection Monographies Hydrologiques, ORSTOM France.

Olivry, J. C., Chouret, A., Vuillaume, G., Lemoalle, J. & Bricquet, J. P. (1996) Hydrologie du Lac Tchad. Monographie hydrologique 12. ORSTOM France.

Rabus, B., Eineder, M., Roth, A. & Bamler, R. (2003) The shuttle radar topography mission – a new class of digital elevation models acquired by space borne radar. *ISPRS J. Photogramm.*, **57**(4), 241–262.



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