Detection of Holocene Lakes in the Sahara Using Satellite Remote Sensing

E.F. Lambin, J.A. Walkey, and N. Petit-Maire

Abstract

During the Holocene warm optimum, the Saharo-Sahelian limit was located at 22° to 23° N latitude, sahelian biotopes and surface water being recorded all across the current southern Sahara. The extension of lakes during the last warm Holocene optimum is related to the range and frequency of monsoonal rains and/or of Atlantic cyclones. Our objective is to produce a record of Holocene surface water extension in an area presently hyperarid. This study demonstrates the feasibility of detecting the localization of paleolakes by analyzing the spectral information of remotely sensed data. The spectral signature of evaporitic deposits related to the drying up of paleolakes is separable in the red and near-infrared wavelengths from the spectral signature of the surrounding land-cover classes. The most appropriate spatial resolution — in the range of resolution cell sizes of current sensors — to discriminate the residual records of paleolakes is 80 metres.

Introduction

Geological and biological evidence in the Saharan basins, east to west, demonstrates that past cold (glacial) global episodes and past warm (interglacial) global episodes have resulted in, respectively, extensions and regressions of the desert belt. The Saharo-Sahelian limit can be defined as roughly corresponding to the 100-mm isohyet. During the Last Glacial Maximum, at 20,000 B.P., this limit was located around 13° to 14° N latitude (Talbot, 1984). During the Holocene warm optimum, this limit was located at 22° to 23° N latitude (Petit-Maire, 1991). Sahelian biotopes and surface water (lakes or swamps) were recorded at those latitudes throughout the large basins from the Atlantic to the Red Sea (Petit-Maire and Kröpelin, 1991). To obtain a synoptic representation of surface water extension in the present Saharan area, there is a need to connect spatially all the local observations. Satellite remote sensing is the most appropriate tool to provide such a coarse scale representation because geological surface features show distinctive spectral patterns on remotely sensed data (Petit-Maire and Page, 1992). In this preliminary study, we test the feasibility of detecting Holocene paleolakes on the basis of the spectral information of remotely sensed data. If this feasibility is demonstrated, we can define the spatial resolution of remotely sensed data that is the most appropriate to detect paleolakes. We shall also attempt, if possible, to characterize by remote sensing their surface and contours.

Radar imaging from space has been used to detect sand-buried channels of ancient river and stream courses in desert environments (e.g., McCauley *et al.*, 1982), but the detection of paleolakes does not necessarily require the ground-penetrating capability of radar systems. Passive satellite remote sensing techniques have never been applied before to the mapping of paleolakes, but a few authors have shown the practicability of fine resolution satellite data in detection of saline soil (Singh *et al.*, 1983; Singh and Dwivedi, 1989; Manchanda, 1984; Sommerfeldt *et al.*, 1985). Some of the minerals formed at the surface of agricultural fields by salinization and waterlogging are the same as found in the residual deposits of paleolakes. Gore and Bhagwat (1991) have shown that highly saline soils correspond on Landsat MSS data to the brightest white patches. These authors could extract different classes of saline areas using a Soil Brightness Index. In the work of Stoner and Baumgardner (1980), soils with gypsic mineralogy, a very common feature for residual paleolake deposits, were also found to have the highest spectral reflectances on average, for all observed wavelengths, among over 240 United States and tropical soil series.

The Holocene Lakes in the Taoudenni Basin (Northern Mali)

In the hyperarid central Sahara, a string of Holocene paleolakes is located along a 125-km long depression, between El Guettara and Taoudenni. A detailed description of these is given by Fabre and Petit-Maire (1988) and Petit-Maire (1991). A brief summary of their main characteristics will be given here.

Between 9000 and 4000 years B.P. ± 500 years, permanent lakes existed in this area. They were fed by runoff and karstic emergences from a limestone Carboniferous plateau to the north, into a flat red clay country. The hydrological optimum was between 8500 and 6700 year B.P. when rainfall seasonality strongly decreased, indicating both monsoonal and Atlantic precipitation patterns. Between 4400 and 3500 year B.P., all lakes dried up, some leaving saline evaporites (Agorgott), others leaving carbonates, still forming visible pillars and yardangs (Haijad), or travertines with gypsum in small depressions (Telig) (Figure 1). The upper layer of the deposits of the Agorgott brackish lake consists of pale red

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sebkha sandy clays with halite brought to the surface by capillary action.

Detection of Paleolakes on SPOT Data

Data

We have processed and interpreted one SPOT image in the multispectral mode covering the Taoudenni area. In that mode, there are three spectral bands (green, red, and near-infrared) with a nominal spatial resolution of 20 metres. These data were acquired on 6 May 1986 in clear-sky conditions and include the three paleolakes described in the last section (Figure 2). The image has been geometrically corrected and registered to the 1:200,000-scale topographic map of Taoudenni in the UTM projection. No atmospheric correction has been performed. A contamination of the satellite image by atmospheric aerosols would only be a problem for this study if the optical thickness of the atmosphere had varied through the scene. As reference data, we have used the photogeologic interpretation of the area (Fabre, 1983); field data from Fabre and Petit-Maire (1988), Fabre (1991), and Oxnevad (1991); and a preliminary study of SPOT images (Page *et al.*, 1991). The digital image processing has been performed with the software PCI EASI/PACE 5.0.

Spectral Separability Measure

A procedure commonly used in remote sensing is to determine, before classifying the data, the mathematical separability of classes. We are particularly interested in knowing how separable the spectral signature of paleolakes is from the spectral signature of the surrounding land-cover classes, defined through field surveys (Fabre, 1991). The spectral response of salts and carbonates has been compared to the response of four other classes: "Red Country-1" (sandstone covered by sand), "Red Country-2" (exposed sandstone), carbonates and Hammadian marls, and Hammadian limestone. To perform the interclass separability analysis, the Jeffries-Matusita (JM) distance (also called the Bhattacharrya distance) has been calculated between the evaporites and the other classes. This distance is a measure of the average distance between two class density functions which have a normal distribution. It has been demonstrated that it performs considerably better as a separability measure for multivariate normal spectral class models than divergence and is equiva-

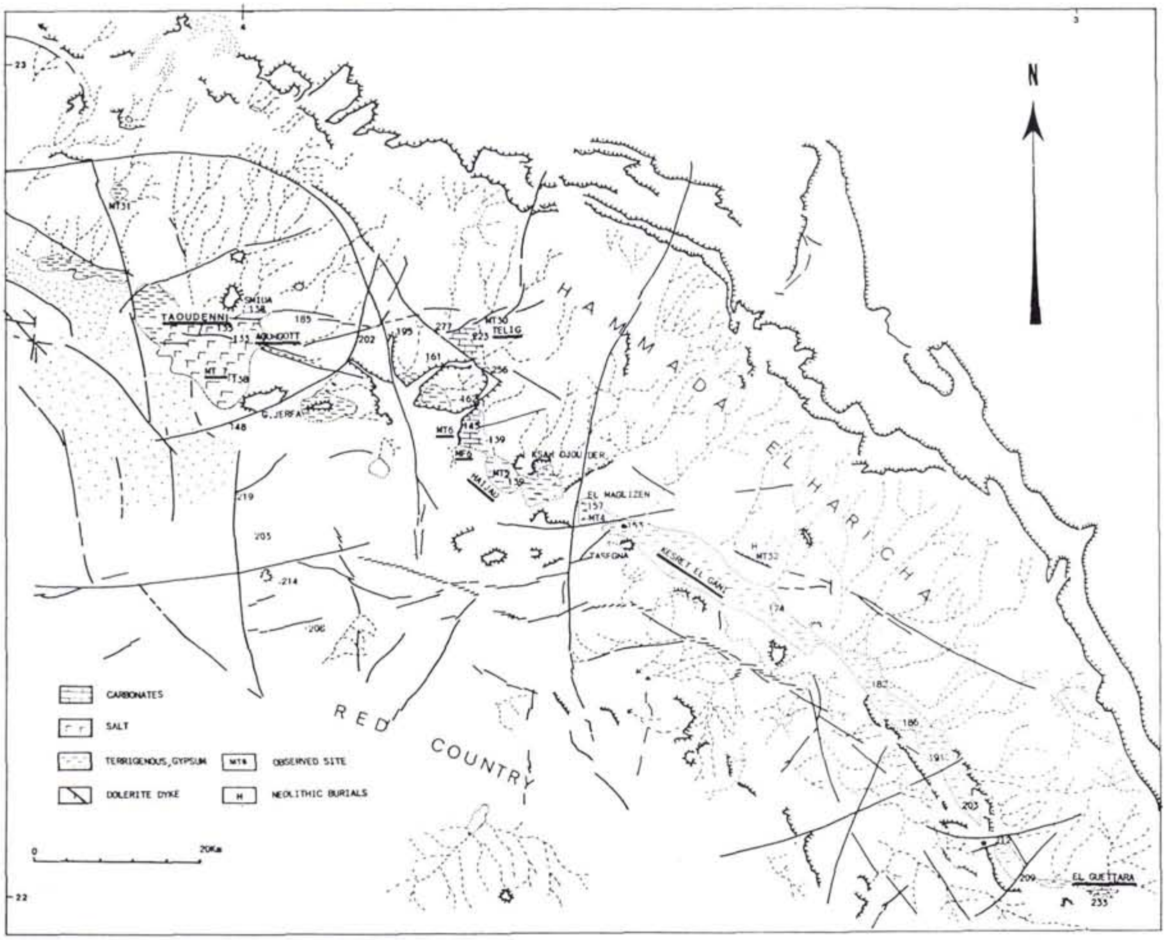

Figure 1. Field map of the area between Taoudenni and El Guettara, with paleolakes location (from Fabre and Petit-Maire, 1988).

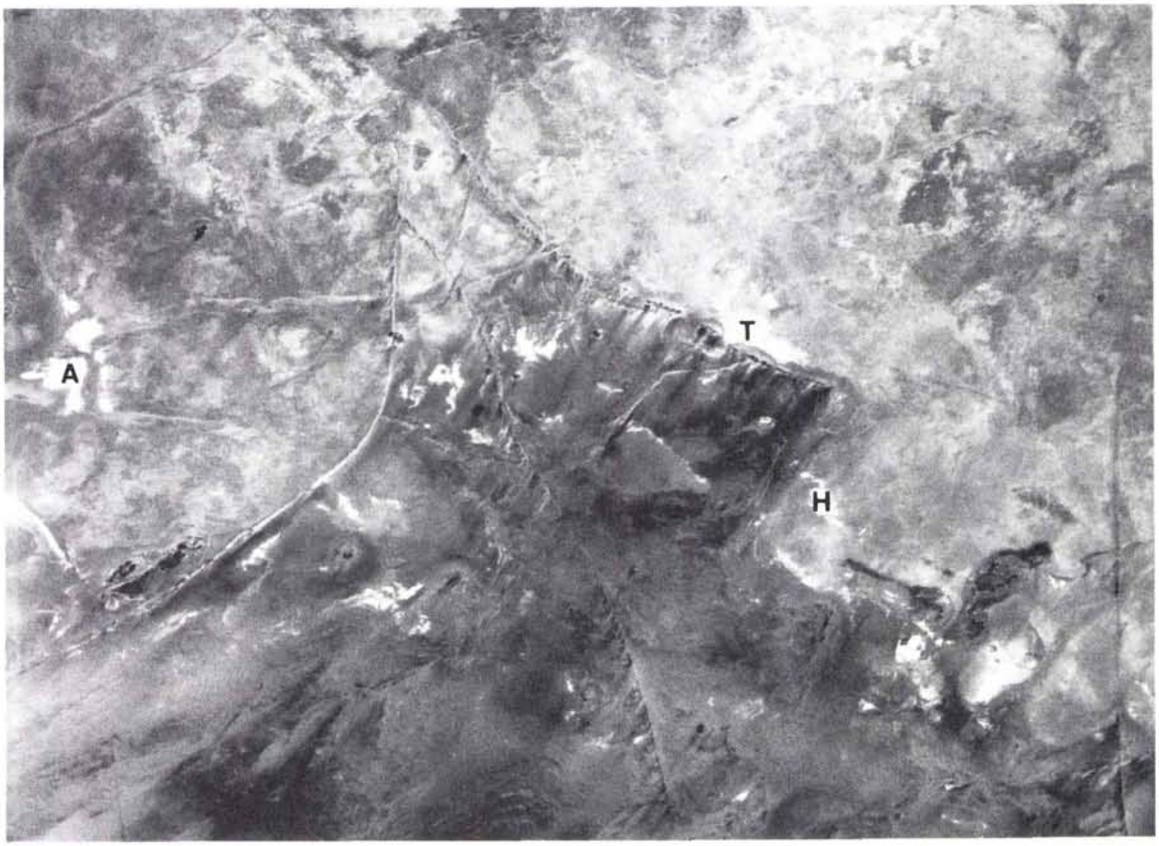

Figure 2. Image subset of the SPOT XS Band 3, with the paleolake locations. Paleolacustrine evaporitic deposits appear as bright white patches. **A** = Agorgott; **T** = Telig; **H** = Haijad. Dikes can be seen as linear features. © SPOT image Copyright 1990 CNES.

lent to transformed divergence (Swain *et al.*, 1971). By contrast to the Mahalanobis distance, the JM distance has a saturating behavior with increasing class separation, as does the probability of correct classification. A JM distance of 2.0 between two spectral classes would imply classification of pixel data into those classes (assuming they were the only two) with 100 percent accuracy, if probability distribution class models are employed and if the density functions are normal (Richards, 1986).

The spectral signatures of the different classes have been defined by selecting training areas from the reference data. Each class was represented by a sample of prototype pixels which have, on the photogeologic map, the attributes of that class. Means, standard deviations, and covariance matrices for the three SPOT bands were extracted for each class, and pairwise JM distances were calculated between evaporites and all the other classes, first, taken individually, and then merged in coarser categories (Table 1).

These results demonstrate that the evaporite and carbonate spectra are highly separable from the spectra of the other classes. It can also be seen that, for the maximum-likelihood classification, the potential for discriminating the evaporites from the rest is larger if the other classes are treated separately rather than clustered together. This is explained by an increase in covariance when dissimilar classes are clustered.

Table 1. Jeffries-Matusita (JM) Distances between Evaporites and the other Classes

	Sand covered sandstone	Exposed sandstone	Carbonates and Hammadian marls	Hammadian limestone	Average JM distance
Evaporites	2.00	2.00	1.951	1.981	1.983
Evaporites	2.00		1.938		1.969
Evaporites		1.951		1.981	1.966
Evaporites			1.904		1.904

Classification

The scatterplot of the red and near-infrared bands has been produced (Figure 3). As can be expected (Crist and Cicone, 1984), most of the pixel data fall along the so-called "soil line" (the diagonal of the scatterplot). All the evaporite pixels are located at the extreme end of the soil line, having the brightest spectral response both in the red and near-infrared wavelengths. This observation suggests that an automatic detection of this class should be possible using the spectral information in these two bands only. A classification of the evaporites spectral class has been attempted using a simple

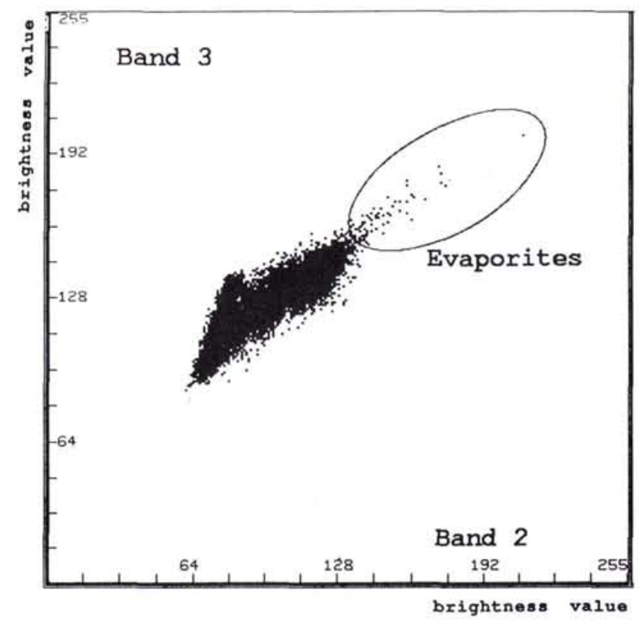

Figure 3. Scatterplot of the red and near-infrared bands.

thresholding of the red and near-infrared bands. This is equivalent to a two-band parallelpiped classification. The third SPOT band was not used in the classification because, for this image, it is highly redundant with the red band (correlation coefficient of 0.96). The photogeologic interpretation of the area has been used to select training areas over several known evaporite deposits. The threshold to extract paleolake pixels has been defined as the value two standard deviations below the mean of the training data for that class, in the two bands. This interval is displayed on Figure 3 and includes about 95 percent of the values of the class. The brightness values of the threshold are 140 in the red band and 159 in the infrared band. All pixels with a spectral response above that threshold correspond to evaporitic pixels. All pixels with a spectral response below that threshold correspond to other classes. This simple approach allowed us to map the extension of the evaporitic deposits.

Evaluation of the Method

Given the great difficulty in performing field work in this part of the Sahara, field data have not been systematically measured at the pixel level, according to a pre-defined sampling scheme and with a location accuracy satisfactory enough to control the satellite-derived map at the pixel scale. However, in addition to the photogeologic interpretation of the area, very good reference data from past expeditions in the Taoudenni basin are available (Figure 1). Therefore, our product was evaluated at the scale of the paleolakes.

Concerning the location of the paleolakes, the classification results were in very good agreement with the reference data. For the estimation of the areal extent of the paleolakes, the evaluation is more complex because the lakes extension has varied throughout the Holocene. However, the areal extent of the apparent evaporitic deposits of the paleolakes, as estimated by remote sensing, can be compared to the total areal extent of the topographical depression, as estimated in the field. These estimates are based on an interpretation of the topography and geology of the landscape (Fabre, 1991), and correspond to the *maximum* limit of the *potential* lake area.

As shown in Table 2, the remote sensing analysis detects the surface features associated with paleolakes but only classifies a small portion of the topographical depressions which are at the origin of these paleolakes. The bright signatures which are extracted by thresholding the red and infrared bands correspond to the surface of exposed salt, carbonate, and gypsum deposits, e.g., the residual records of the past lake extension. This approach gives only a *minimum* figure of the past lake surface, and therefore leads to omission errors. The surface of the topographical depression sets the upper limit of the lake extension, but this does not mean that the lake necessarily filled the whole depression at one period of the Holocene. This raises the question of what are the real limits of the paleolakes, knowing that there have been significant variations of the lake level throughout the Holocene (Fabre, 1991). If the threshold to discriminate the bright evaporite deposits is lowered, a commission error is produced: pixels corresponding to the Hammadian carbonates and limestone at the northeast of the lake boundaries are included in the class at the same time as pixels within the lake depression.

Discussion

In summary, the location of residual evaporitic paleolake deposits by remote sensing is feasible, using a simple thresholding of the red and near-infrared bands. This classification technique can be easily automated to process a large amount of satellite data in order to detect paleolakes over a much wider area of the Sahara. Concerning our second objective, the characterization by remote sensing of the surface and contours of paleolakes, the results are disappointing. While it is not possible, with the field data currently available, to quantify the magnitude of our omission error, it is likely to be large when considering the maximum *actual* lake extension, which is unknown but assumed to be approximate to the area of the topographic depression. This underestimation is explained by the fact that evaporites do not cover the entire extent of the original lake surface due to the original physical process of evaporite formation and to the subsequent aeolian deflation of evaporite deposits.

Optimal Spatial Resolution

In order to estimate the cost, in terms of data acquisition and processing, of mapping evaporite deposits throughout the Sahara, it is important to determine what is the optimal resolution-cell size to discriminate the residual records of paleolakes. The selection of an optimal spatial resolution and

TABLE 2. COMPARISON OF THE ESTIMATED RESIDUAL EVAPORITIC AREA WITH THE TOTAL SURFACE OF THE DEPRESSIONS AT TELIG, HAIJAD, AND AGORGOTT

	Area of the depression	Satellite estimation of exposed evaporites	Proportion of the depression area
Telig	7.3 km²	0.2 km²	2.74%
Haijad	55.0 km²	6.0 km²	1.09%
Agorgott[1]	52.3 km²	2.91 km²	5.56%

[1] Estimations only for the portion of the lake which is on the SPOT image (44% of the total area of the lake).

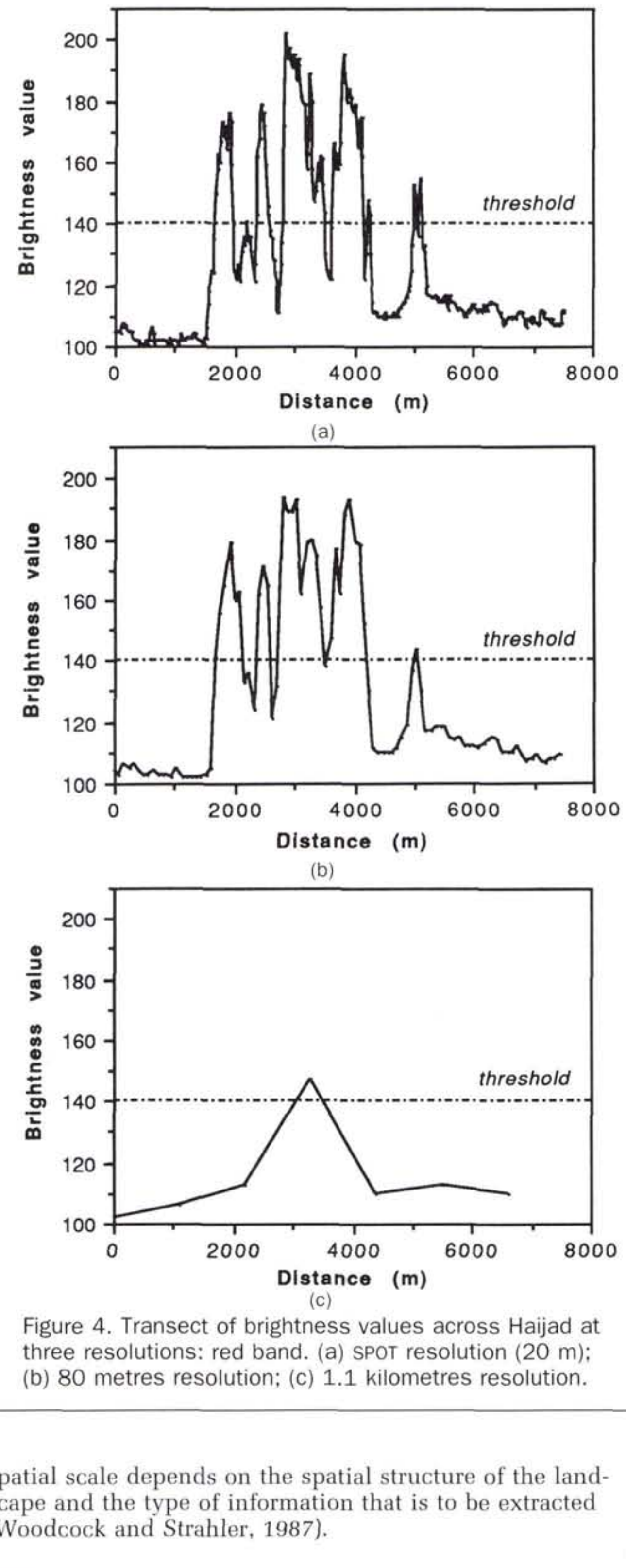

Figure 4. Transect of brightness values across Haijad at three resolutions: red band. (a) SPOT resolution (20 m); (b) 80 metres resolution; (c) 1.1 kilometres resolution.

spatial scale depends on the spatial structure of the landscape and the type of information that is to be extracted (Woodcock and Strahler, 1987).

Method

The SPOT data have been analyzed at their original spatial resolution (20 metres in the multispectral mode) and have then been degraded to successively coarser resolutions, approximating the response of other satellite sensor systems: 80 metres (Landsat Multispectral Scanner) and 1.1 kilometres (AVHRR LAC/HRPT data). Landsat Thematic Mapper data have not been simulated because their spatial resolution (30 metres) is only slightly coarser than the resolution of SPOT data. The simple aggregation and averaging of SPOT pixels do not produce a perfect simulation of the actual Landsat and AVHRR data, because these sensors are characterized by different point spread functions, modulation transfer functions, and spectral resolutions. However, this study only explores ranges of resolutions and there is no need to mimic exactly the response of particular sensors. At every resolution and for every paleolake, the data have been reclassified using the same threshold values, and the new maps have been compared to the map produced at the 20-metre resolution.

Results

The results demonstrate that, among the spatial resolutions of current satellite sensors, the 80-metre range (Landsat MSS) will lead to the highest classification accuracy. To illustrate this point, brightness values at three resolutions have been plotted along an east-west transect which crosses the topographical depression and the evaporitic deposits of the Haijad lake, a medium size paleolake. The different transects are shown on Figure 4 for the red band, and Figure 5 for the infrared band. At the SPOT resolution (Figures 4a and 5a), the brightness values along the transect exhibit many local variations, especially through the evaporite deposits (brighter pixels). This is consistent with the findings of Woodcock and Strahler (1987) who have shown that, when the resolution-cell size is much smaller than the object to be discriminated, the local variations of brightness values corresponds to changes in scene composition at a scale finer than the scale of the object. This within-class variance decreases the spectral separability of the evaporite class and results in a lower classification accuracy. At the 80-metre resolution (Figures 4b and 5b) some of the within-lake variation has been smoothed by the averaging effect related to the larger resolution-cell size. The spectral separability of the paleolake will thus be higher at this resolution. At the 1.1-kilometre resolution (Figures 4c and 5c), only one pixel has a value larger — but only slightly — than the threshold in the red band and, in the near-infrared band, the paleolake is barely detectable. This resolution is therefore too coarse compared to the size of the lake: most of the 1.1-km pixels fall across evaporitic deposits and surrounding materials, and average their brightnesses values. The presence of these mixed pixels removes the possibility of locating evaporite deposits reliably. Any smaller or narrower paleolake would stay undetected. As a conclusion, the most appropriate spatial resolution in the range of resolution cell sizes of current sensors is 80 metres.

Conclusion

The digital analysis of remotely sensed data could detect and locate the evaporitic deposits related to the drying up of paleolakes through an empirical analysis of radiances in the red and infrared wavelengths. Even though we demonstrated that the areal extent of paleolakes cannot be estimated, their simple detection and location remains a useful application, especially if applied at the scale of tropical deserts. It will allow an inventory of previously unknown paleolakes to be made. From that, it will be possible to infer changes in atmospheric paleocirculation based on the presence of surface water and modifications of the Precipitation/Evaporation ratio. This will contribute to the improvement and test of cli-

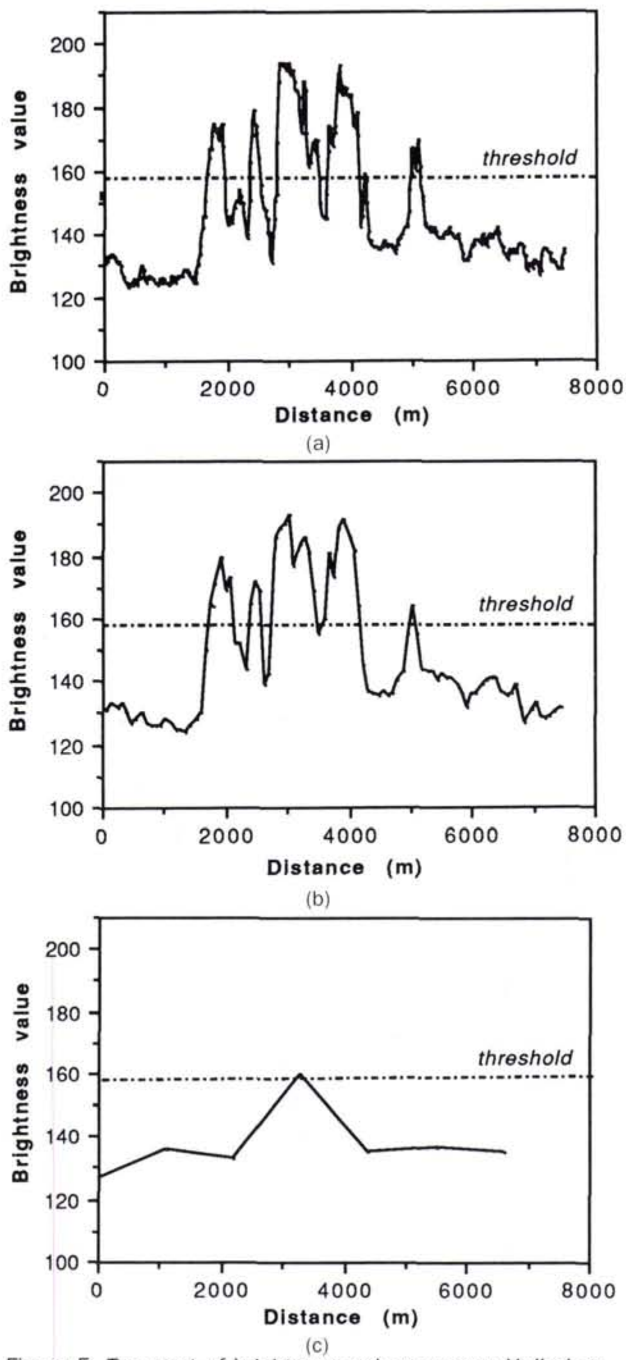

Figure 5. Transect of brightness values across Haijad at three resolutions: near-infrared band. (a) SPOT resolution (20 m); (b) 80 metres resolution; (c) 1.1 kilometres resolution.

matic models. In order to map and quantify the *extension* of surface water during the humid optimum, remote sensing techniques will have to be combined with field surveys or aerial photointerpretation for a finer estimation of the actual past surface of individual lakes. The project of detecting and locating most Holocene paleolakes in the now arid part of northern Africa would involve the processing of a very large amount of data. In order to cover the region lying between 30° and 17° N, from the Atlantic shore of Mauritania and Occidental Sahara to the Red Sea shore of Sudan, the handling of 300 Landsat MSS scenes would be required.

In addition to its contribution to paleoclimatology, the method presented here has potential applications in archaeology. The presence of surface waters in the present Sahara, as in other dry areas, attracted animal and human populations. Many Holocene lacustrine shores are rich in archaeological sites. The detection of paleolakes can therefore be used to locate privileged sites for field investigations.

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