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APPLICATION OF AVHRR TO MONITORING A CLIMATICALLY SENSITIVE PLAYA. CASE STUDY: CHOTT EL DJERID, SOUTHERN TUNISIA.

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ABSTRACT

The importance of monitoring changes in the levels of lakes within endorheic basins using remotely sensed data as a means of assessing changes in regional aridity is noted. Large salt playas are highlighted as ephemeral lakes that can display extreme sensitivity to changes in regional rainfall patterns, and which commonly do not have extensively managed catchments. To explore the application of high temporal frequency monitoring of salt playas using remote sensing, the Chott el Djerid, a large salt playa situated in southern Tunisia was targeted. A short time series of 39 Advanced Very High Resolution Radiometer (AVHRR; resolution 1·1 km at nadir) images of the Chott el Djerid (spanning 36 months between 1987 and 1990) were compiled along with climate information from a weather station at Tozeur. Using image histogram manipulation, lake areas were extracted from the time series. A good level of agreement was observed between recorded rainfall events and the presence of surface water on the playa, and for a limited sample of large flood events it was found that there were significant relationships between rainfall, evaporation and estimated lake areas ($r^2 = 98{\cdot}5$, $p < 0{\cdot}001$). Overall, these data suggest that contemporary lake formation is largely controlled by temporal changes in effective precipitation within the basin. In addition, it was found that the coefficient of variation of the time series, and a combination of temporal reflectance profiles extracted from it, could be used to give a direct indication of which sedimentary surfaces on the playa are affected by large flood events, and the extent to which these events may be preserved within the recent sedimentary record at these sites.

KEY WORDS: closed basin; playa; lake area; AVHRR; Chott el Djerid

INTRODUCTION

Closed playa basins

In low latitudes the dominant climatic signal is commonly related to changes in the regional precipitation regime. However, in many contemporary studies, regional climatic patterns have been difficult to assess by direct measurement, and tend to fall below the scale of data emanating from general circulation models (Palutikof *et al.*, 1996). Indeed, both past and present rainfall or pluvial signals within these regions have been found to be best indicated and preserved by studying changes in the level and chemistry of closed or 'non-outlet' lakes (Street-Perrott, 1985; Street-Perrott and Harrison, 1985; Roberts, 1990; Mason *et al.*, 1994). As a result, most palaeoenvironmental and contemporary studies aimed at understanding climatic changes within the same latitudes have recognized the importance of monitoring changes in closed-basin lake volumes as a means of indirect assessment of regional aridity (Birkett, 1995).

Salt playas are common features of closed, arid basins. Although these environments represent only a small proportion of modern drylands (*c*. 5 per cent; Cooke *et al.*, 1993) and a minor proportion of sediments within the geologic record, they are important because their sediments, if interpreted properly, often record the sensitive interrelation between regional changes in climate patterns and tectonic activity within continents (Bryant, 1996). Such interpretation of palaeoenvironmental or pluvial records from

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playas, and their relationship to regional climate, salinity, temperature and the hydraulic balance of the lacustrine system depend critically on the understanding of factors such as: (1) processes leading to lake evolution; (2) processes recording lake evolution; or (3) processes that may destroy or modify palaeoenvironmental records. However, our understanding of the dynamic response of playas to changes in climatic inputs is poorly understood, ultimately hindering our understanding of lake evolution and processes leading to sediment modification. In addition, an incomplete knowledge of energy variables, brine geochemistry, watershed and hydrological characteristics, and varying contribution from surface runoff and aquifer(s) that occur in these playa environments may also affect the success of the contemporary and palaeoenvironmental study of salt playas (Teller and Last, 1990).

One possible reason for such gaps in our understanding of these environments is that the dynamics and location of playas often pose particular problems to researchers studying and understanding both contemporary and past sedimentary records (Bryant, 1996). Indeed, most ephemeral changes in lake volumes by flood events can be both violent and relatively short lived: in 1974 a single flood brought 39·3 km^3 of water into the Lake Eyre basin, Australia, but 39·5 km^3 of water was removed during the next two years by evaporation (Kotwicki, 1986). An additional problem in interpreting changes in the volumes of closed, arid basins is that the vast majority have a significant groundwater inflow, the rate of which may have changed over time. It is therefore important to understand the response of contemporary closed playa basins to current short-term changes in rainfall patterns and judge the effect of groundwater inflow to lake volumes. To do this we need to be able to monitor contemporary hydrologic and sedimentary changes at appropriate spatial and temporal scales using remote-sensing techniques (Drake and Bryant, 1994; Bryant, 1996).

Remote sensing of closed lake basins

Generally, most remote-sensing studies of playas using satellite-borne data (e.g. Landsat TM/MSS and ERS-1/2 SAR; Millington *et al.*, 1989, 1995a; Bryant, 1996; Drake *et al.,* 1994; Wadge *et al.*, 1994) have recognized the inherent inability of the sensor/platform combinations to fully account for the temporal dynamics of the sedimentary surfaces over a suitable time period. Consequently, changes within closed basins as a result of possible changes in regional rainfall patterns (e.g. extreme rainfall events) have been almost impossible to monitor due to either: (1) the coarse temporal resolution of the data (Townshend *et al.*, 1989); or (2) the cost or availability of scenes spanning multiple dates (Millington *et al.*, 1995a).

An alternative approach, utilizing meteorological satellite data (NOAA-AVHRR: National Oceanographic and Atmospheric Administration, Advanced Very High Resolution Radiometer) with a higher temporal resolution (but coarser spatial resolution: 1·1 km at nadir) in a preliminary study of large Tunisian lakes and playas was taken by Drake and Bryant (1994). Similarly, Harris, (1994), Harris and Mason (1989), Birkett (1995) and Birkett and Mason (1995) have focused on the importance of rapid temporal monitoring of changes in large perennial closed-basin lake volumes by remote sensing and have used a combination of both optical sensing (AVHRR/ATSR) and radar altimetry (derived from ERS-1 and TOPEX/POSEIDON sensors) in order to measure closed lake levels and areas. In particular, the advantages of the use of optical AVHRR data are that: (1) readily available AVHRR imagery of large closed basins can be obtained from extensive image archives on the same daily/monthly basis as regional climatic data; and (2) the data lend themselves to the simple differentiation of water bodies within closed, arid basins.

However, in contrast to many perennial closed basins, playas commonly demonstrate rapid changes in lake area and volume largely in response to relatively extreme regional rainfall events. Also, because of their remote location and saline/hypersaline brines, these environments are less prone to excessive anthropogenic alteration to contemporary and past catchment water balance, thus ensuring a reliable climatic signal. Nevertheless, with the exception of work undertaken by Drake and Bryant (1994) on playas in Tunisia, and Prata (1990) on the 1985 flood of Lake Eyre, most large arid basins or playas, although crucial to our understanding of dryland climate fluctuations within low latitudes, are or have not been monitored on a regular basis, seemingly as a result of the inherent difficulty in utilizing and interpreting their record.

With this in mind, this research aims to build upon these studies, and show the results of the application of AVHRR data prior to and during a high magnitude (1:20) event (Bryant *et al.*, 1994a) on a salt playa in North Africa for which the basin hydrochemistry, sedimentology and groundwater inflow are largely understood, and for which some climatic data were available. In addition, an attempt will be made to quantify spatial reflectance changes in response to climatic inputs with a view to future monitoring of playa basins, and possible site selection for palaeoenvironmental investigation.

STUDY AREA

Location

The Chott el Djerid, in southern Tunisia, is a contemporaneous terrestrial, evaporitic environment that has been the subject of intense sedimentological and hydrochemical studies (e.g. Coque, 1962; Mamou, 1976; Meckelein, 1977; Gueddari *et al.,* 1983; Millington *et al.,* 1989; Bryant *et al.,* 1994a,b; Drake *et al.,* 1994). It is an ephemeral salt playa situated in an arid-zone closed basin which has a catchment area of 10 500 km^2 (Gueddari *et al.*, 1983). The Chott el Djerid itself has a surface area of approximately 5360 km^2 (Millington *et al.,* 1989), and is situated at a latitude of around 34°N (see Figure 1). The Chott el Djerid basin forms the northeastern and one of the lowest extremities of the Bas Saharan Basin. This artesian basin covers most of the Algerian and Tunisian Sahara and extends to Morocco and Libya, enclosing the whole of the Grand Erg Oriental (Roberts and Mitchell, 1987). The Bas Saharan Basin is composed of a series of complex aquifers in the underlying and surrounding sediments which emerge at the surface in the Zone of Chotts (Figure 1). Chott el Fedjadj receives discharge from the Cretaceous *Continental Intercalaire* aquifer via upward percolation through its base. The Chott el Djerid is one of the major discharge areas from the *Complexe Terminal* aquifer, which is made up of Turonian dolomites, Upper Senononian limestones and evaporites, and in places the Mio-Pliocene sands and conglomerates. The water emerges into the Chott el Djerid through a thin clayey aquiclude of Quaternary age (Roberts and Mitchell, 1987).

Alternations of wetter and drier periods throughout the Pleistocene and Holocene in this part of Tunisia have been recognized for some time (e.g. Coque, 1962; Coque and Jauzien, 1967). However, the interpretation of climate change in this period and its relation to sediments, specifically lake shoreline deposits found within the Chott el Djerid basin, have become more controversial in recent times (Richards and Vita-Finzi 1982; Rognon, 1987; Causse *et al.* 1989; Fontes and Gasse, 1989).

Climatic data from Tozeur

Detailed climate data for the period 1985–1990 were collected from the meteorological station at Tozeur, bordering the western edge of Chott el Djerid (Figure 1). The mean annual temperature is 21°C, and evaporation, which is highest between May and September, has a mean annual value of 1500 mm. The mean annual rainfall for Tozeur is approximately 140 mm. During the study period, however, annual rainfall was generally below this (27–90 mm), with an exception occurring in 1990 (328 mm; Figure 2). Inspection of the mean monthly rainfall totals for the years leading up to 1990 (Figure 2) reveal the seasonal nature of rainfall events within this region, with most rainfall occurring in the winter months: 70 per cent between the months of October and March (Table I). The months between April and September are generally characterized by low rainfall (<30 mm in total), mean monthly temperatures of between 20 and 35°C, and extremes of evaporation ranging from 150 to 300 mm per month.

From 21 to 23 January 1990 a weak depression was situated over southern Tunisia as a result of an influx of polar air from eastern Europe (Ouezdou *et al.,* 1990). This resulted in exceptionally wet

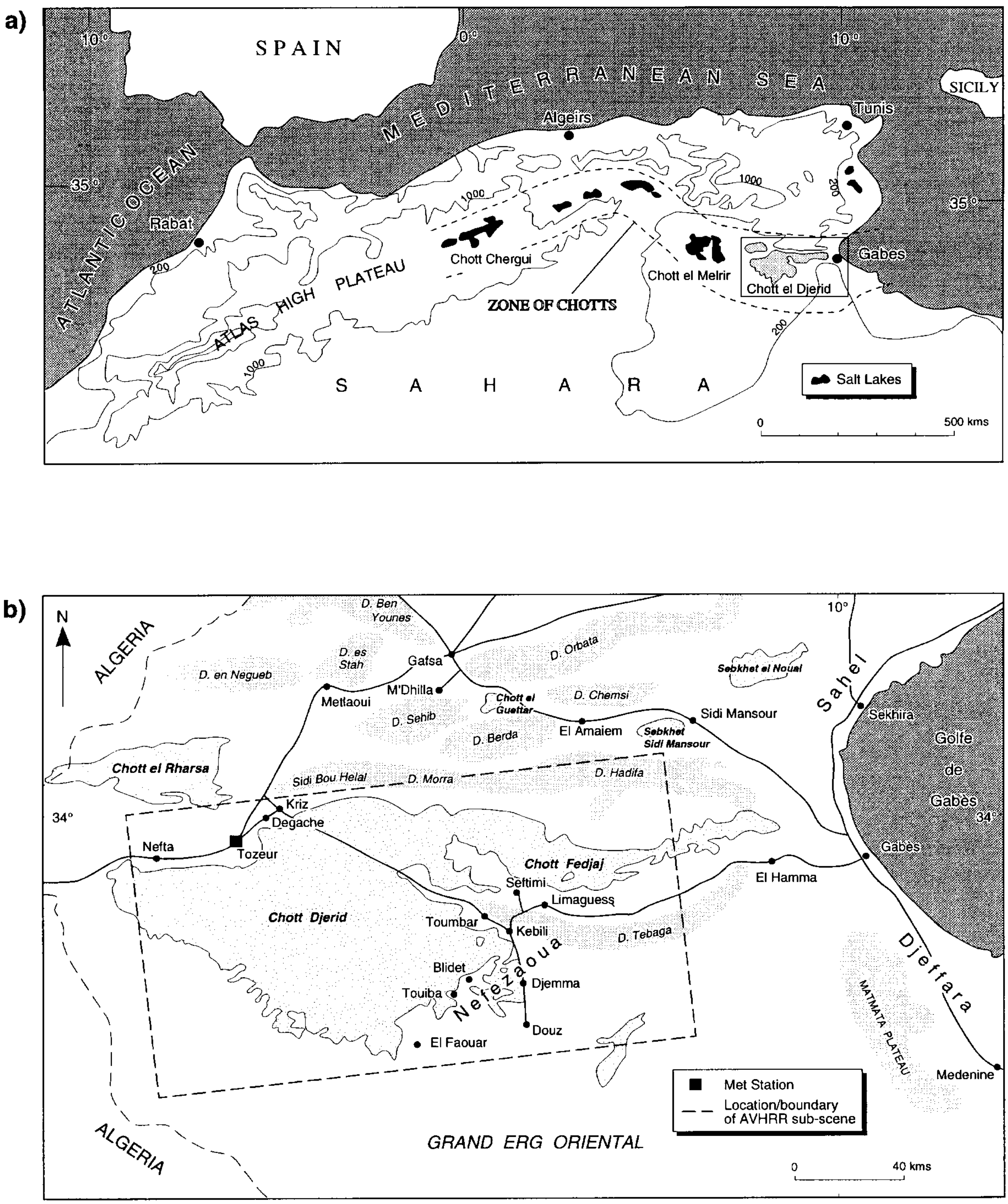

Figure 1. (a) Map of North Africa showing the location of the Zone of Chotts. (b) Enlarged map showing the location of the Chott el Djerid basin, southern Tunisia (after Bryant *et al.*, 1994)

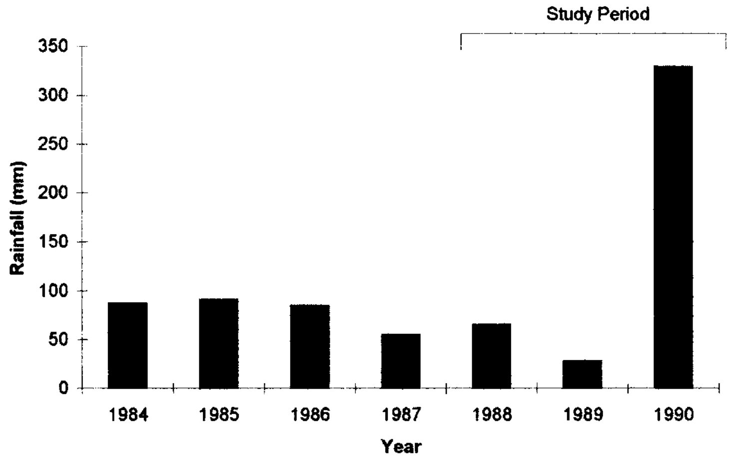

Figure 2. Graph of rainfall data from the Tozeur meteorological station, 1985–1990

Table I. Total monthly rainfall measured at Tozeur from 1985 until just before the 1990 flood, with an estimate of mean monthly contribution to a total year's rainfall within the same time period

Month	Total rainfall (mm) 1985–1990	Average rainfall (mm) 1985–1990	Contribution (%)
Jan	44·20	8·84	10·79
Feb	11·90	2·38	2·91
Mar	46·50	9·3	11·36
Apr	44·60	8·92	10·89
May	60·50	12·1	14·77
Jun	9·80	1·96	2·39
Jul	0·70	0·14	0·17
Aug	9·90	1·98	2·42
Sep	26·20	5·24	6·40
Oct	53·10	10·62	12·97
Nov	40·40	8·08	9·87
Dec	61·70	12·34	15·07

conditions, and precipitation over these three days varied from eight to 50 times the mean monthly average (or 0·5 to four times the annual mean) depending on location (Figure 2). At Tozeur, almost 140 mm of rainfall fell over the course of three days. Runoff within southern Tunisia in January 1990 was estimated to be $2{\cdot}2 \times 10^9$ m^2, equivalent to six times the annual mean (Ouezdou *et al.,* 1990). Rainfall events of this magnitude in the Chott el Djerid basin have a repeat cycle of approximately 20 years, the last recorded event of this magnitude being in 1969 (Ballais, 1973). The combined effect of the high rainfall and runoff events led to the formation of an ephemeral lake on the Chott el Djerid (Bryant *et al.*, 1994a).

Hydrochemistry and surface mineralogy

The hydrology and hydrochemistry of the Chott el Djerid were studied in detail after the flood of January 1990 (Bryant *et al.,* 1994a,b). Dilute inflow waters were found to have a meteoric or groundwater origin, their chemistry reflecting dissolution and weathering of ancient Triassic, Cretaceous

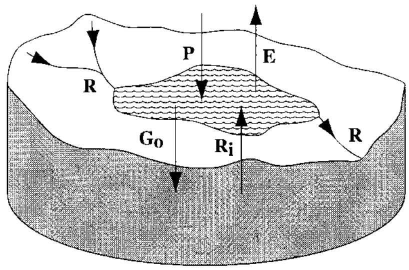

Figure 3. Schematic diagram of the hydrological balance of a lake system. Where R = Runoff, D = Discharge, P = Precipitation, E = Evaporation, Gi = groundwater Inflow, and G_o = Groundwater Outflow. For a closed system in equilibrium conditions, D = G_i = G_o = 0 (modified after Mason *et al.*, 1994)

and Mio-Pliocene evaporites within the basin and the two major aquifers that resurge into it (Bryant *et al.,* 1994a). The resulting brine type existing after gypsum precipitation on the playa was found to be of a Na–K–Mg–Cl–SO_4 type. The predicted stable mineral assemblage to form from the evaporation of brines on the surface of the Chott el Djerid was found to include gypsum ($CaSO_4.2H_2O$), halite (NaCl) and carnallite ($KMgCl_3.6H_2O$). Of these phases halite was expected to be the dominant phase at the centre of the playa as a result of recycling of the pre-existing halite-dominated salt pan by dilute inflow waters.

The range of evaporite phases present on the surface of the Chott el Djerid was also studied in September 1990. In agreement with hydrochemical results (Bryant *et al.,* 1994a,b) a mineral assemblage dominated by halite, carnallite and gypsum was observed. Halite and very small, ephemeral deposits of carnallite associated with brine pools made up much of the central saline pan facies, and thin gypsum and halite efflorescent crusts were observed on the saline mudflat. Clastic material (calcite, quartz and some aeolian gypsum) was largely found on the saline mudflat and playa margin facies (Bryant *et al.,* 1994b).

Hydrological balance of the Chott el Djerid

Dynamic changes within a playa basin generally result from the interaction of surface water, sediments and groundwater. The hydrological component of this change for most lake systems can be defined specifically in terms of changes to the hydrological balance (see Figure 3). Using time-averaged data, this can be expressed as follows:

$$\frac{\delta V}{\delta T} = R - A_L(E_L - P_L) - D + G_i - G_o \qquad (1)$$

where R = runoff, D = discharge, P_L = precipitation, E_L = evaporation, G_i = groundwater inflow, G_o = groundwater outflow, V = lake volume, and A_L is the area of the lake. For most closed systems that display hydrological equilibrium, G_o, G_i and D are assumed to sum to zero, and thus, Equation 1 can be rewritten as:

$$\frac{\delta V}{\delta T} = R - A_L(E_L - P_L) \qquad (2)$$

However, on the Chott el Djerid we have a change to this equilibrium state, where Gi is quite significant, and losses from the system due to D can be expected to be minor. As a result, the hydrological balance for the playa can be modified to:

$$\frac{\delta V}{\delta T} = R - A_L(P_E) + G_i \qquad (3)$$

where P_E is the effective rainfall over the lake per unit area (evaporation (*E*) minus precipitation (*P*)). Under time-stable conditions (i.e. where $\delta V/\delta T = 0$) the equation can be rewritten as:

$$A_L \propto G_i/P_E \qquad (4)$$

Mason *et al*. (1994) also show that if a range of assumptions are taken into account, AL can be further related to a regional aridity index (*C*) by the following equation (where AC is the total catchment area)

$$A_L/A_C = C \qquad (5)$$

The above hydrological balance equations give good insight into the dominant hydrological controls on lake formation within closed systems. However, if groundwater inflow (*Gi*) to the Chott el Djerid is assumed to be constant, then under time-stable conditions the main control on the presence of surface water within the basin should be variations in *PE*. However, for much of the time, $E > P$ on the Chott el Djerid, leading to a largely negative *PE*. The sensitive balance between *PE* and *Gi* within the Chott el Djerid has long been recognized (Causse *et al*., 1989). Indeed, many of the important lake shore-line deposits recording major changes in lake level within the basin (and proposed changes in *C*) have been attributed to past changes in *PE* (from negative to positive values) resulting in fluctuations between fresh-water and hypersaline conditions (Causse *et al*., 1989).

From contemporary observations made on the Chott el Djerid, Coque (1962) indicates the importance of both *PE* and *Gi*, but suggests that surface water influxes are largely subordinate to groundwater influxes from the two main aquifers (Drake and Bryant, 1994), and that, as the Chott el Djerid is a playa with a groundwater province considerably larger than its topographic basin, fluctuations in groundwater level should be largely controlled by the balance between artesian recharge and evaporation. This is supported by observations of surface water on the Chott between 1947 and 1958 (Coque, 1962; Drake and Bryant, 1994) and some contemporary observations which show that during most years at least part of the basin is covered between the months of November and February, a period in which aquifer resurgence within the basin is most likely to be greater than evaporation. However, although probably constant until the last century, the flow from the two aquifers has been observed to have reduced significantly as a result of systematic abstraction over the last 100 years (Mamou, 1976). In 1900 the estimated yield from natural springs in the Nefzaoua area was $660\,l\,s^{-1}$, with the first artificial borehole yielding $604\,l\,s^{-1}$. Further borehole abstraction has reduced the yield of these springs to $560\,l\,s^{-1}$ by 1950, and $250\,l\,s^{-1}$ by 1976. Such a documented reduction in groundwater inflow (G_i) suggests that seasonal lake formation resulting from positive P_E may be less common at present than in the period prior to extensive aquifer abstraction. Indeed, Drake and Bryant (1994) suggest a reduction in flooding ratio (in terms of presence/absence of surface water) within the basin from 32 per cent in the period from 1948 to 1965, to 23·5 per cent between 1985 and 1987. Nevertheless, the magnitudes of past lake level changes within the Chott el Djerid basin suggest that temporal changes in P_E may still be considered as an important factor affecting both past and present lake formation within the basin.

METHODS

Data acquisition and pre-processing

This study uses high-resolution picture transmission (HRPT) AVHRR images of Tunisia which have a spatial resolution of 1·1 km at nadir. Given the importance of the 1990 flood to the hydrology of the Chott el Djerid, 39 images, spanning 36 months, were collected for the period January 1988 to December 1990 (Table II). Images were collected for dates when there was minimal cloud cover over most of Tunisia. Multiple data were collected for selected months in order to account for some inter-month

Table II. Details of the 39 AVHRR images collected for use in this study

Date	Code	Overhead time (LST)	Sensor view angle from nadir (°)	Solar zenith angle (°)
02 Jan 88	T_1	14·11	16·7	70·6
09 Feb 88	T_2	14·05	3·1	63·3
27 Mar 88	T_3	14·13	9·4	51·8
06 Apr 88	T_4	14·06	–2·8	47·8
03 May 88	T_5	14·17	10·3	44·1
13 May 88	T_6	14·10	–1·9	41·1
27 Jun 88	T_7	14·28	18·3	42·3
27 Jul 88	T_8	14·06	–17·6	40·0
04 Aug 88	T_9	14·20	2·4	44·0
09 Sep 88	T_{10}	14·34	17·6	54·3
18 Oct 88	T_{11}	14·15	–15·6	61·6
12 Nov 88	T_{12}	14·47	25·7	72·5
22 Dec 88	T_{13}	14·16	–22·9	71·8
12 Jan 89	T_{14}	13·16	42·7	62·9
05 Mar 89	T_{15}	12·55	20·1	47·0
16 Apr 89	T_{16}	12·30	–18·5	29·8
06 May 89	T_{17}	12·27	–23·9	23·9
15 May 89	T_{18}	12·35	–13·4	23·2
11 Jun 89	T_{19}	12·59	20·3	24·6
01 Jul 89	T_{20}	12·54	12·2	23·7
01 Aug 89	T_{21}	12·35	–17·5	24·1
17 Sep 89	T_{22}	12·49	0·8	39·7
02 Nov 89	T_{23}	13·11	27·2	57·0
26 Jan 90	T_{24}	13·13	25·6	60·0
15 Feb 90	T_{25}	13·01	5·9	53·4
23 Mar 90	T_{26}	13·15	24·4	43·5
04 Apr 90	T_{27}	12·47	–17·9	35·8
26 May 90	T_{28}	13·26	32·3	30·9
08 Jun 90	T_{29}	12·45	–24·8	22·1
22 Jun 90	T_{30}	13·33	37·4	31·1
26 Jun 90	T_{31}	12·50	–14·6	23·3
04 Jul 90	T_{32}	13·03	–1·9	25·5
21 Jul 90	T_{33}	13·18	19·0	29·9
31 Jul 90	T_{34}	13·09	5·7	29·7
11 Aug 90	T_{35}	12·50	–23·5	28·7
14 Sep 90	T_{36}	13·19	15·9	42·8
22 Oct 90	T_{37}	13·03	–12·3	53·0
26 Nov 90	T_{38}	13·19	6·5	63·0
31 Dec 90	T_{39}	13·31	22·2	65·8

variability. Field data were collected within the playa basin throughout 1990 in conjunction with hydrochemical investigations, and daily rainfall records for 1990 were obtained for the meteorological station located at Tozeur. The AVHRR images were processed using a proven sequence of pre-processing algorithms. First, the data from channels 1 and 2 were atmospherically corrected using an algorithm developed by Singh and Saull (1988) to reduce the effects caused by atmospheric molecules and variations in scan geometry. Second, areas of cloud contamination were detected and highlighted using the thermal-infrared data (channel 5; 11·5–12·5 μm). Finally, each image was geometrically corrected (accuracy of <1 pixel) in order that equivalent geographic points coincided on each scene, which ensured that each of the field sites could be accurately located on the imagery, and that the data were directly comparable with those used by Drake and Bryant (1994).

Image analysis: lake formation and area estimation

Determining the area of a lake within a closed, evaporitic basin using coarse resolution remote-sensing data can be problematic. The water reflectance properties of AVHRR bands 1 and 2 are contrasting, as radiation absorption by water increases with wavelength (Drake and Bryant, 1994). Consequently radiation detected by band 1 penetrated water to a depth of approximately 2 m, and band 2 to a depth of 0·4 m (Prata, 1990). Given that lake depths on the Chott el Djerid were rarely greater than 2 m, data from band 2 were felt more effective for the determination of surface water area. A number of methods employing AVHRR band 2 have been used, ranging from simple histogram manipulation (Harris and Mason, 1989), mean vector reflectance (Drake and Bryant, 1994) and image classification (Prata, 1990) to more sophisticated image segmentation procedures (Harris, 1994; Harris and Mason, 1989). Given the relative insensitivity of the Drake and Bryant (1994) approach (incorporating a *mean reflectance vector* and relatively straightforward *flooding ratios*), and problems locating areas of permanent, deep water necessary for the formulation of reliable *discriminant functions* in the approach used by Prata (1990), the method of Harris and Mason (1989) was felt most appropriate in this instance.

Using this approach, lake area determination is based upon the assumed symmetrical nature of the edge-pixel water fractions within an image histogram for band 2 of AVHRR. To demonstrate the method, the image and histogram for band 2 of T_{25} are shown in Figure 4a and b. Surface water pixels are represented by peak A on the image histogram, and mudflat pixels are represented by peak B. Essentially, lake area measurement is undertaken by placing an automatic threshold at the halfway point between peaks A and B, and extracting the count for pixels to the lake side of the threshold (Barker, 1975). In order to remove any contributing pixels to peaks A and B from outside of the playa margin, the method was modified by calculating the histogram using a close-fitting Boolean mask. The modified histogram can be seen in Figure 4c, and the resulting lake area image in Figure 4d. Assumptions associated with this method identified by Harris and Mason (1989), and modified here, are: (a) that the edge pixel distribution is symmetrical about the mid-point between the mudflat and water, and that the difference in widths of the land and water peaks has no affect; (b) the mudflat (or water) distribution does not extend past the mid-point between the peaks; and (c) the mudflat and water within the edge pixels have the same distributions as the overall mudflat and water distributions.

In applying this approach, Harris and Mason (1989) and Harris (1994) have also shown that it is important to acknowledge systematic difficulties associated with accurate lake-area measurement, particularly in relation to the lake margin. First, with regard to lake size, Harris (1994) suggests that for lakes of approximately $100\,km^2$, up to 20 per cent of the lake area can be contained in edge pixels. However, Harris and Mason (1989) were able to demonstrate that the lake area for Loch Neagh, Northern Ireland (with an open area of $390\,km^2$) could be determined with an accuracy of approximately 1 per cent. Second, the precipitation of soluble salts at the edge of an open, evaporating saline lake may affect the reflectance characteristics of the lake margin (Harris, 1994). Finally, vegetation concentrations may be relatively high around the margins of saline lakes, thus affecting the reflectance characteristics of the lake margin (Harris, 1994). Of these factors, both lake size and salt precipitation are deemed to be most important, as the ephemeral lake generally borders a saline mudflat which is largely devoid of vegetation.

Although lake area validation is important in assessing the contribution of these factors, in this preliminary study no high-resolution data (e.g. Landsat TM, SPOT-XS or radar altimeter) were available to undertake a true validation of the extracted lake-area estimates (Drake and Bryant, 1994), and give an indication of possible methodological errors.

Image analysis: temporal reflectance signatures

In order to augment lake-area estimates for the 1988–1990 period, and determine the dynamic sensitivity of different process domains to hydrologic inputs within the closed basin, a range of temporal signatures was extracted from the time series. In essence, the aim of this technique is to characterize sedimentary processes from reflectance profiles in the same manner in which temporal AVHRR-derived NDVI profiles from similar time-series data have been utilized to determine plant community dynamics (e.g. Peters *et al.*, 1997). As a framework for sample site location, it was deemed important to

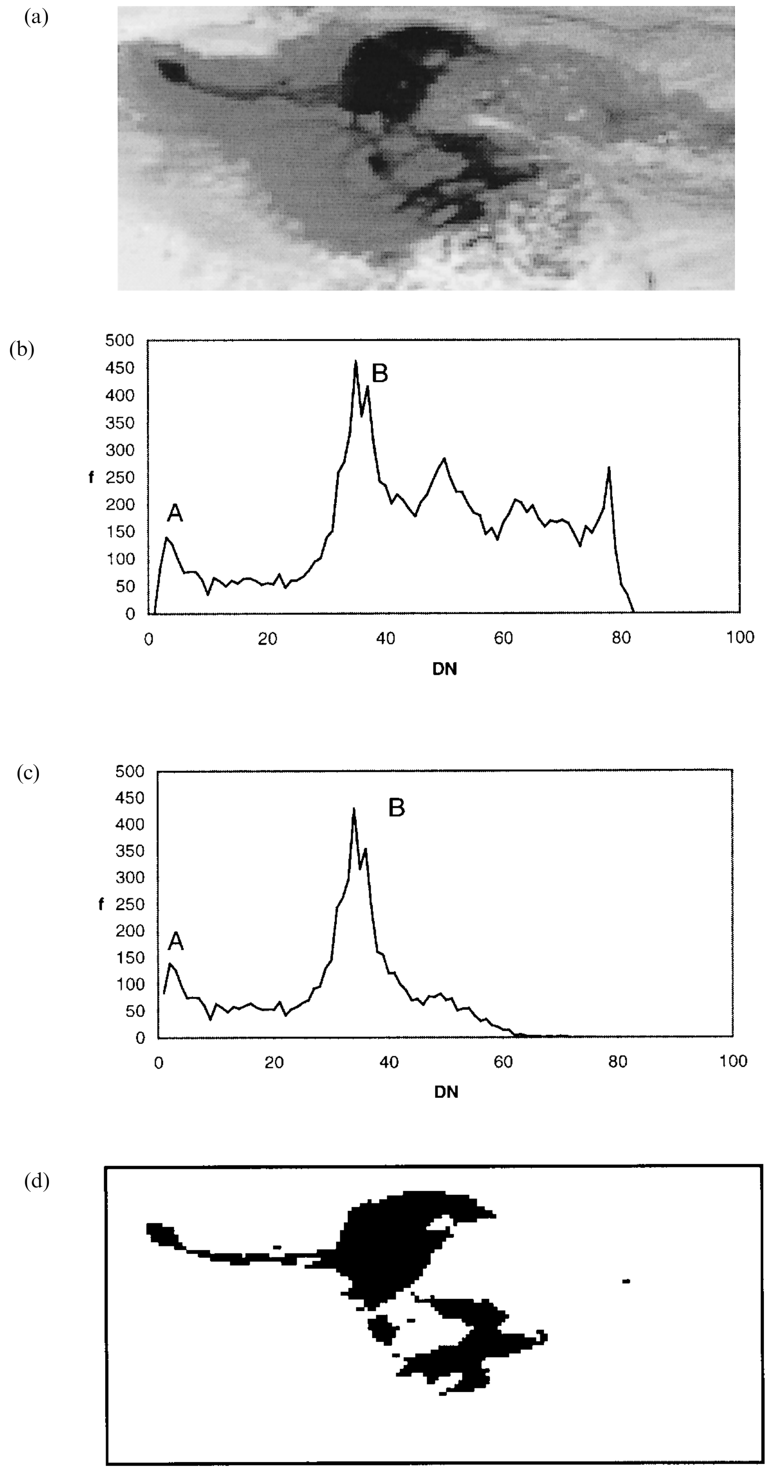

Figure 4. (a) Atmospherically and geometrically corrected AVHRR band 2 image of the study area (see Figure 1.) for January 1990. (b) An image histogram for the same image showing the lake (peak A) and mudflat (peak B). (c) Image histogram of the same image with a Boolean mask applied. (d) Extracted lake area image resulting from the application of the peak splitting algorithm

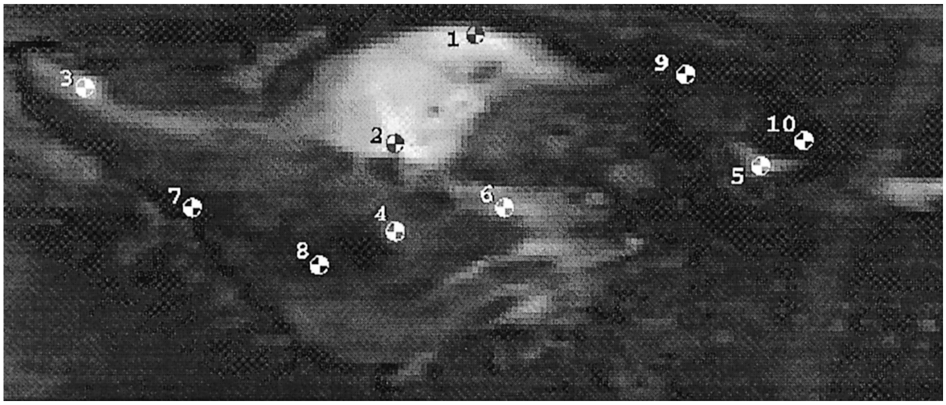

Figure 5. Coefficient of variation (*CV*) image for the Chott el Djerid. Lighter tones represent high *CV* values (*c.* 0·5), and darker tones low *CV* values (*c.* 0·1)

concentrate on three levels of sedimentary surfaces: (i) those that were highly dynamic, and thus most affected by flooding and salt precipitation (e.g. the salt pan); (ii) those that were stable and relatively unaffected by flooding and salt precipitation, but more prone to aeolian deflation (e.g. the saline mudflat); and (iii) those that were of intermediate status (playa margin).

In order to define surface instability/stability, an indication of temporal reflectance variability within the time series was needed. One simple measure of variance within a data set is the coefficient of variation (*CV*), which is the standard deviation of a data set expressed as a percentage of the mean value (Sokal and Rohlf, 1981). These values were therefore calculated for the time series, again using a Boolean mask to remove pixels outside the study area, and the range of values within the playa interrogated. An image of spatial *CV* can be seen in Figure 5. Consequently, using these data, 10 temporal profiles were extracted from the time series in order to represent areas of differing surface variance within each process domain. In addition, points were also chosen in areas affected by contrasting hydrological inputs.

RESULTS AND DISCUSSION

Lake-area estimates

Figure 6a details the lake areas on the Chott el Djerid during the study period, showing a reasonable correspondence between the presence of surface water ($>1\,km^2$) on the playa and specific rainfall events recorded at Tozeur. Initially, this suggests that the assumptions adopted when extracting lake areas from imagery were largely valid.

Analysis of lake-area estimates for 1988, a year of below-average rainfall (65·1 mm), shows that the presence of surface water on the playa occurs only after rainfall events that coincide with periods of relatively low monthly *E* (30–90 mm; January, October and December). In contrast, combined rainfall events totalling 17·8 mm in April, a period of significantly higher *E* (158 mm), resulted in no recorded surface water on the image for that month. In 1989, an exceptionally dry year of below-average rainfall (27·5 mm), no surface water was recorded at all. These results suggest that evaporation levels within the Chott el Djerid basin between April and September play an important role in inhibiting lake formation.

Analysis of lake areas from 1990, a year of extreme rainfall events, shows a different pattern. The maximum lake area observed during the study period was immediately after the flood of January 1990 (*c.* $1358\,km^2$) when the existing salt pan was almost completely dissolved. Subsequent evaporation rapidly reduced the lake area to $727\,km^2$ by March accompanied by salt precipitation on the lake

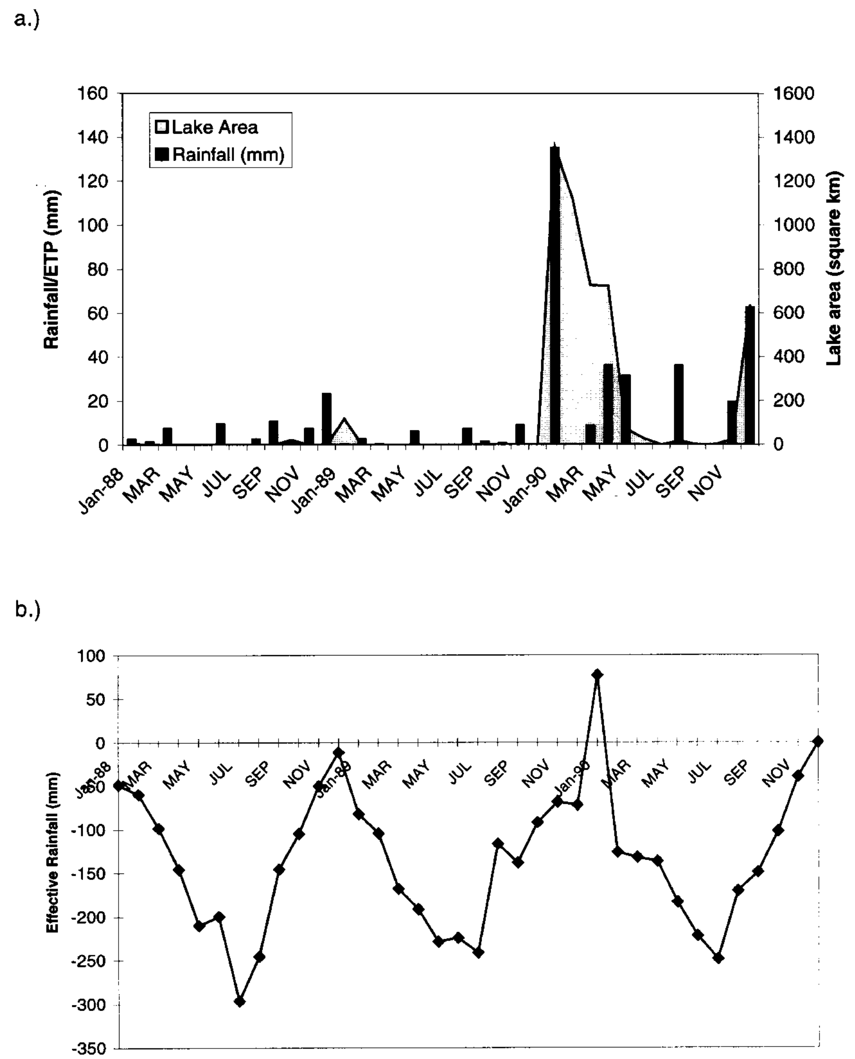

Figure 6. (a) Rainfall and lake areas recorded on the Chott el Djerid (1987–1990). (b) Effective rainfall on the Chott el Djerid (1987–1990)

margin. Further evaporation of the lake was then affected by relatively heavy rainfall in March (8·9 mm), April (35·9 mm) and May (31·2 mm). However, despite these further inputs, the lake was found to have evaporated to dryness by the end of June (the period of maximum E), precipitating a large halite-dominated saline pan. This progression from ephemeral lake to salt pan is in agreement with observations throughout 1990 of lake evaporation and salt precipitation made by Bryant *et al.* (1994a).

In the period June–November 1990 the playa returned to the dry hydrologic equilibrium witnessed throughout 1989. This was partially truncated by a short-lived flood in August stemming from three days of rainfall (28·5 mm) prior to image collection for that month. In this case, the rapid evaporation of surface water is clearly a result of extreme E levels (Figure 6b). Finally, in November and December 1990 more extensive areas of surface were again recorded on the playa as a result of rainfall events coinciding with periods of much lower E (Figure 6b).

It can therefore be seen that lake formation on the Chott el Djerid corresponds more closely to rainfall events that coincide with periods of relatively low monthly evaporation (<100 mm) in the months October to March, and also with the period of greatest rainfall probability (Figure 6b). The rainfall

Table III. Summary of selected rainfall events (1987–1990) which resulted in the formation of a lake on the Chott el Djerid.

Date	Rainfall (mm)	Evaporation (mm)	Lake area (mm)
Jan 1988	9·8	51	7
Oct 1988	12·3	106	22
Dec 1988	23·0	34	118
Jan 1990	135·2	58	1358
Aug 1990	35·8	205	17
Nov 1990	19·3	58	23
Dec 1990	62·5	62	627

events of January 1988 and January 1989 which resulted in lake formation, even though P_E values were negative (–42 mm and –11 mm), suggest that G_i can contribute positively to the surface hydrology within these months. The occasional rainfall events that fall outside of this period do not seem to result in extensive lake formation as a result of extreme evaporation (e.g. the events of August 1990). The simple estimates of lake area do, therefore, largely confirm the supposed relationship between effective rainfall inputs (P_E) and lake formation on the Chott el Djerid outlined earlier, and further help to explain the observations of Coque (1962) and Drake and Bryant (1994).

Factors affecting flood magnitude

To understand the specific relationship between rainfall (P_E) and detected lake area (A_L), seven specific rainfall events were extracted from the time series along with corresponding lake-area estimates from image data collected during the month in which flooding occurred (Table III). Lake areas representing the subsequent evaporation of lakes, and those affected by additional rainfall inputs (e.g. during 1990), were not included. The extracted data were then subjected to a least squares regression test (Sokal and Rohlf, 1981).

Owing to the initial skewed nature of the extracted data, the values were subjected to a log-transform before analysis, resulting in near-normal distributions (Anderson–Darling p-values $>0{\cdot}8$). Initially, therefore, even though the sample size is small ($n=7$) a significant relationship (valid at the 0·05 level) can be seen to exist between the $\log_{10}$ of A_L and the $\log_{10}$ of P, yielding an r^2 of 0·79 (Figure 7). In addition, if the monthly evaporation rate (E) is added to the simple regression analysis, the relationship between the variables is further strengthened, yielding a result with an r^2 of 0·90 that is significant to the 0·001 level (Table IV). However, even though the relationships observed are statistically significant, the data extracted are still far from perfect. Indeed, without suitable validation it has to be accepted that a proportion of the lake-area estimates of less than 100 km^2 are likely to have some degree of uncertainty, however small. Essentially, a longer time series of imagery, perhaps incorporating observations from data spanning 10 years, would most likely allow more confident relationships to be determined between these variables.

Nevertheless, even if the brevity of the time series is taken into account, these data suggest that most of the observed lake-area changes on the Chott el Djerid can largely be explained through variations in the following equation (where a and b are constants):

$$\log_{10} A_L = a \log_{10} P - b \log_{10} E \qquad (6)$$

This equation stresses the importance of effective rainfall inputs (P_E) to lake areas within the Chott el Djerid basin, which in turn implies that for short-term observations, G_i and R may be subordinate to P_E in their relative effect on lake area and volume changes. Whether P_E has been such a dominant hydrological variable over longer time spans is debatable. Nevertheless, these results show that over

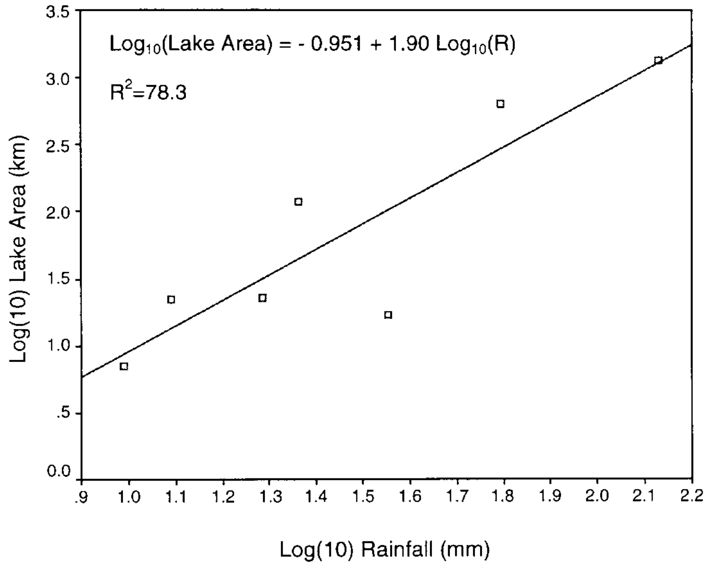

Figure 7. Graph showing the relationship between $\log_{10}$[rainfall] and $\log_{10}$[detected lake area] for selected rainfall events

Table IV. Summary of linear relationships between climatic variables measured at Tozeur, and lake area estimates derived from AVHRR data.

Line fit	r^2
(1) *Lake area* = –36·9 + 11·1 (*P*) – 1·49 (*E*)	98·7
(2) Log_{10} (*Lake area*) = 1·21 – 1·19 Log_{10} (*E*) + 1·92 Log_{10} (*P*)	90·3
(3) *Lake area* = –168 + 11·3 (*P*)	95·8
(4) Log_{10} (*Lake area*) = 0·951 + 1·90 Log_{10} (*P*)	78·3

short time spans the magnitude and frequency of large floods on the Chott el Djerid are a function of regional rainfall phenomena, and not simply seasonal changes in groundwater inflow. Consequently, the contemporary detection of lake areas (and perhaps volumes) within the Chott el Djerid using monthly remote sensing may give a direct and rapid assessment of rainfall inputs into the basin, and thus a potential method for observing future changes in *C* (see Equation 5) within southern Tunisia.

Temporal reflectance profiles

The first two profiles taken from the Chott el Djerid (Figure 8a) were extracted from points on the central salt pan facies of the playa that exhibited high *CV* values (1 = 0·525, 2 = 0·499). The causeway that crosses the saline pan and separates the two points was built in the early 1980s in order to connect the towns of Kibili and Tozeur. The Chott el Djerid north of the causeway is fed by the catchment bounded by the Djebel Sidi bou Hellal, and the Chott el Fedjadj (Figure 1). To the south of the causeway the catchment is more extensive, ultimately being bounded by the Grand Erg Oriental. The elevation of the sediment surface on either side is marginally different, being on average 0·2 m higher on the north side than the south (Drake and Bryant, 1994), suggesting differential sediment inputs. From Figure 8a, the January 1988 rainfall event can be seen to only affect point 2 to the south of the causeway. In contrast, the January 1989 event can be seen to affect the points both north and south. This suggests

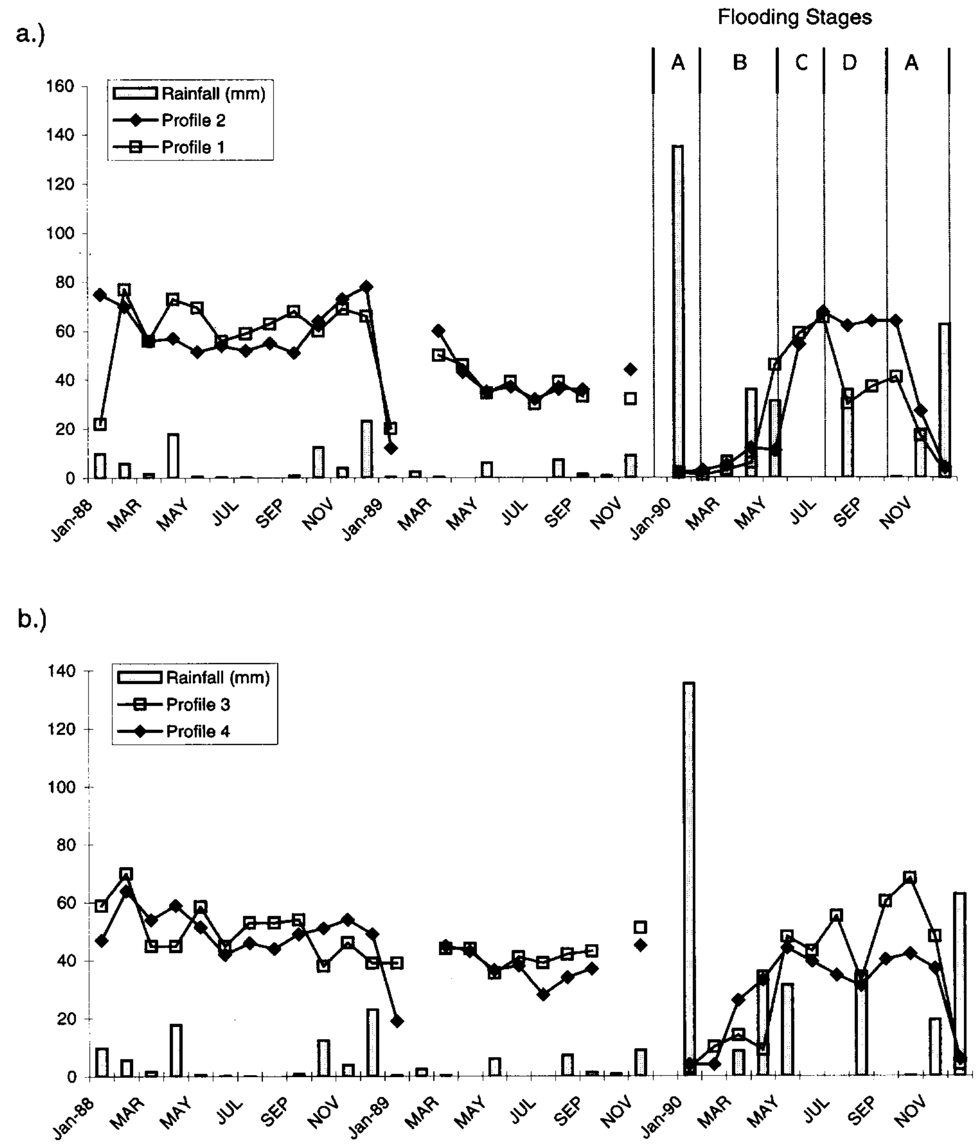

Figure 8. (a) Temporal profiles for points 1 and 2 superimposed on monthly rainfall figures. Gaps in the profiles represent actual gaps in the image time series caused by the lack of cloud-free data for certain months. (b) Temporal profiles for points 3 and 4. (c) Temporal profiles for points 5 and 6. (d) Temporal profiles for points 7 and 8. (e) Temporal profiles for points 9 and 10

that the central facies may be separated into two sub catchments, resulting in a relatively fine dividing line between rainfall events that affect the southern catchment and those that affect the north catchment, or both together. In January 1990, as would be expected from such a large event, the flood affected both points in a similar fashion. However, subsequent differential drying rates can be seen at each point for the lake that formed (south evaporated to dryness quicker than north), perhaps being a function of different lake depths on either side of the causeway.

The importance of these profiles can also be seen in the fact that they record very closely the saline pan cycle of flooding, evaporative concentration and desiccation outlined by Lowenstein and Hardie

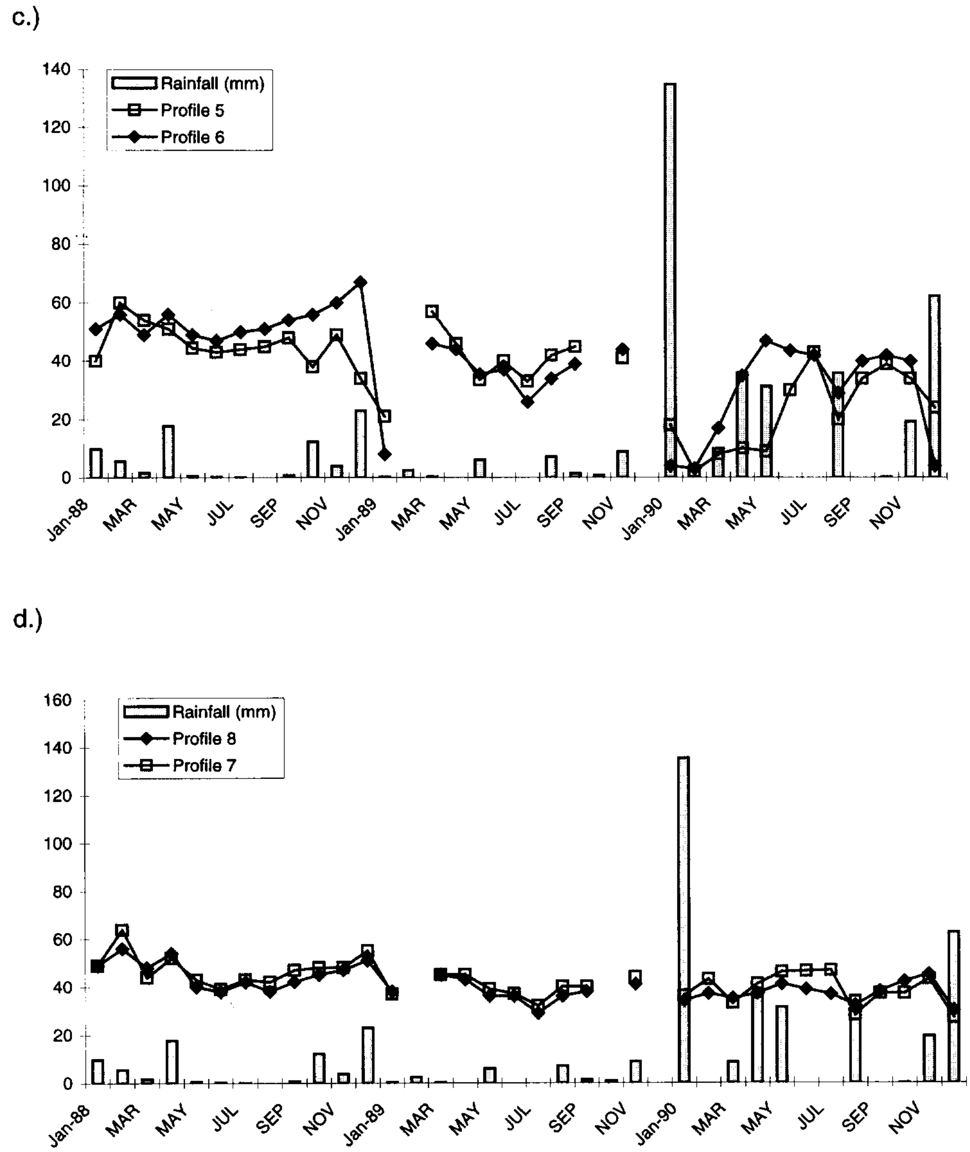

Figure 4. – continued

(1985) and Bryant *et al.* (1994a). From Figure 8a the individual flooding stages suggested by Bryant *et al.* (1994a) (A = flooding, B = evaporative concentration, C = brine pool, D = desiccation) can be seen to relate to characteristic reflectance values (especially for point 1). It is therefore possible that the sediments at these locations may record the discrete flood events affecting them. However, the degree of preservation of saline pan evaporite deposits that record extreme flood events is thought to be a direct function of the chemical maturity of the saline pan, and the relative stability of the water table beneath it. Generally, immature saline pan sediments are heavily reworked during each flood event. However, Lowenstein and Hardie (1985) suggest that after each successive flood event, the shallow groundwater beneath the saline pan will increase their solute concentration, as brines derived from saline pan dissolution sink into the water table. This process can eventually lead to more extensive salt precipitation, and less dissolution or reworking of the pan sediments during successive flood events. From this study, the saline pan of the Chott el Djerid would seem to be of a relatively immature type, as

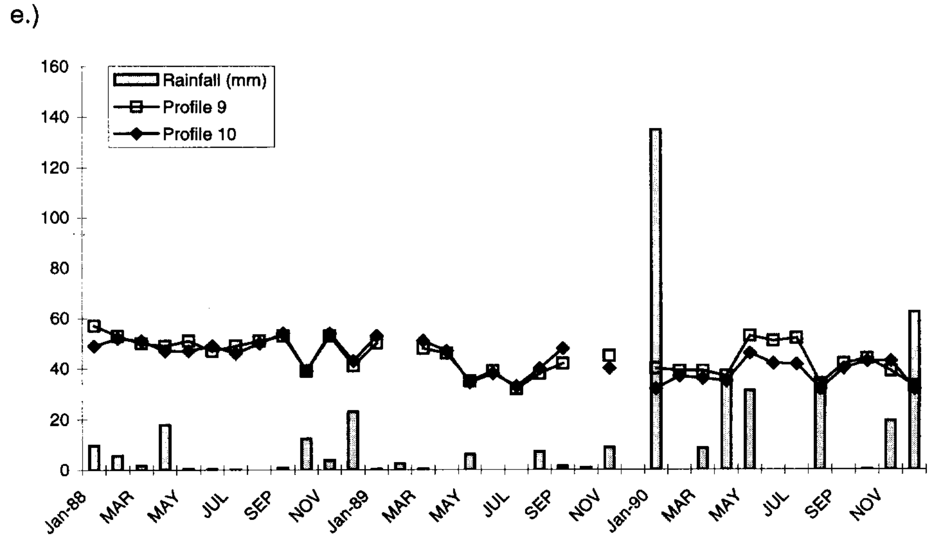

Figure 4. – continued

the extensive halite-dominated central facies was observed to be almost completely dissolved and reprecipitated during and after the floods of 1990 (Bryant, 1993; Bryant *et al.*, 1994a). This would suggest that even at locations within the pan that experience repeated flooding and salt precipitation, preservation of these events is unlikely to be continuous within the shallow sediments.

Profiles 3 and 4 (Figure 8b) represent temporal reflectance curves for points outside the salt pan that demonstrated a reasonably high *CV* (3 = 0·380, 4 = 0·351). Profile 3 represents a small sub-basin located in the western arm of the Chott el Djerid, directly south of Tozeur. Throughout 1988 and 1989 this point demonstrated fairly constant reflectance (40–60DN), seemingly only affected by the January 1989 event. In 1990 this location gives some further indication of the nature and distribution of inflow waters as its reflectance was affected by all of the rainfall events recorded at Tozeur. In addition, it can be seen that during the initial flooding in January 1990 the sub-basin was connected to the central lake by a single channel, which was later isolated as the central lake evaporated, and contracted in area. Subsequently, the high reflectance values recorded between July and October 1990 suggest that a halite crust was precipitated. In contrast, profile 4 represents a large aioun (or salt karst chimney; Bryant, 1993). As a result, it would be expected that this point is sensitive to both aquifer resurgence and local groundwater recharge. In most cases this can be seen to be true, as the reflectance of the aioun reduces with rainfall inputs in a similar manner to profile 3. However, being an area of dilute inflow, the aioun should not experience extensive salt precipitation. Consequently, upon desiccation of the lake in 1990, profile 4 recorded significantly lower reflectance values than profile 3, signifying less extensive halite precipitation.

Profile 5 (Figure 8c) represents the reflectance profile for an area of lake formation in 1990 within the Chott el Fedjadj catchment, just to the north of the village of Seftimi (Figure 1). The temporal profile for this location demonstrates the effect that rainfall events recorded at Tozeur to the east have on Chott el Fedjadj catchment. Generally, most large monthly rainfall totals greater than 20 mm recorded at Tozeur result in a reduction in reflectance at this site. No other events are recorded, which suggests that the climatic records at Tozeur collected during the study period are reasonably representative of the whole basin. Profile 6 is located within the southeastern arm of the Chott el Djerid, directly west of the town of Kibili. Generally, this profile has a very similar progression to that seen in profile 4 (aioun), except for more extensive periods of flooding (lower reflectance) and subsequent halite crust precipitation (increasing reflectance) throughout the study period. Again, good correlation can be observed between dilute inflows recorded in both profiles.

Profiles 7–10 (Figure 8d and e) represent the reflectance properties of areas of saline mudflat within both the Chott el Djerid and Chott el Fedjadj that display low *CV* values ($<0{\cdot}18$). These sedimentary surfaces are less commonly inundated than the central facies, and have more dilute shallow groundwaters. In each case it can be seen that the reflectance profiles for these locations are fairly constant, being partially affected by the large rainfall events of 1990, but not by marked increases in reflectance associated with subsequent salt precipitation. During the 1990 flood a series of distribution channels can clearly be seen within the saline mudflat, generally running into the central lake from the south and from Chott el Fedjadj. This is consistent with these areas having a slightly higher elevation than the central saline pan facies, and suggests that sediments from within these zones are actively recycled during large flood events by fluvial activity. This is a common feature of playas that are located within basins of greater extent than can be filled by extreme floods. In the case of the Chott el Djerid, most of these sedimentary surfaces represent areas that would have been covered by the perennial lakes that existed within the basin during the Pleistocene and Holocene (Coque, 1962). In addition, these data confirm that the sediment records at these locations within the Chott el Djerid are not sensitive to contemporary flood events, and will most likely be dominated by periods of low sedimentation, and seriously affected by both fluvial and aeolian reworking.

From these data it can be seen that the interaction between rainfall events and different sedimentary surfaces is both spatially and temporally complex. However, profiles of changes in monthly reflectance record the detailed response of specific locations to dilute inflows and can help unravel the specific response of a surface to hydrologic inputs. In addition, it can be seen that spatial changes in *CV* within the Chott el Djerid are a reasonably accurate measure of the extent to which a surface or process-domain is affected by dilute inflows. Surfaces with a high *CV* have been shown to be those that experience lake formation and subsequent salt precipitation. In contrast, surfaces with a low *CV* are unlikely to be affected by lake formation, and are generally sites of deflation or erosion. The extent of spatial and temporal variance therefore gives a sensitive indication of surface dynamics and the nature of sedimentary and hydrological processes that may occur. This can in turn provide a useful framework for contemporary palaeoenvironmental investigations within the playa basin.

CONCLUSIONS

1. Using a simple image histogram manipulation technique, estimates of lake area on the Chott el Djerid can be readily extracted from AVHRR band 2 data. In order to validate these estimates, corresponding high-resolution data are required.
2. The recorded presence of surface water on the Chott el Djerid can be related to rainfall events recorded at climate stations bordering the Chott el Djerid basin. However, it was found that flooding is most likely to occur when rainfall events coincide with months that have a relatively low loss due to evaporation.
3. Although largely groundwater-fed, the estimated magnitude of flooding observed on the Chott el Djerid in the period 1987–1990 was found to be largely controlled by changes in the balance between monthly rainfall and evaporation. As a result, future observation of lake area and the catchment flooding ratio within the Chott el Djerid may give an indication of changes in regional rainfall patterns within southern Tunisia.
4. The dynamic response of process domains on the Chott el Djerid to high magnitude rainfall events was found to be both spatially and temporally complex, being a direct function of (a) flood magnitude, (b) spatial location of rainfall event, and (c) surface movement of water (by channel flow or aeolian activity).
5. Temporal reflectance profiles for specific locations can allow the detailed response of a sedimentary surface to hydrologic inputs to be analysed.
6. The *CV* of a particular point within the image time series was a reliable indicator of the extent to which it was affected by flooding and subsequent evaporite precipitation during the study period.

This factor can be used to infer the location of process domains, and thus gain an understanding of which sediments may record a full flooding cycle.

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