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Geomorphology of the upper Inland Niger Delta

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Remote sensing and field mapping formed the basis for a morphological study of the upper Inland Niger Delta, centered on the region surrounding Jenne and Mopti, Mali. The area is characterized by a mosaic of floodplain deposits and soils related to the annual flooding of the Niger and Bani Rivers, with aeolian features of varying ages superimposed. Many morphological features of this area have been related to past shifts in Sahelian climate, with documented past episodes of drought reflected in several generations of dunes that occur in the area. Field and remote sensing evidence indicates that some aeolian materials may be contemporary, and that significant changes have occurred in surface characteristics, colour and in the morphological processes operating during the past 20 years of drought.

Introduction

The drainage basin of the Niger River extends over more than 2,000,000 square kilometres of the Sahel of West Africa. The river rises in the Futa Jalon Highlands of Guinea, only 250 km from the Atlantic coast of Sierra Leone, and flows generally northeastward to the base of the volcanic Adrar des Iforas near the Mali–Algeria border. Just southwest of the Adrar des Iforas, the Niger River bends southward and flows through Niger and Nigeria before emptying into the Gulf of Guinea. Throughout most of its 4,200 km length the river exhibits the sinuous, single-channel form typical of mature rivers in arid regions. However, approximately 800 km northeast of its headwaters in Guinea, the Niger breaks into the broad floodplain complex of anastomosing channels which form the Inland Delta (Fig. 1).

The lack of rainfall in the Sahel since the onset of drought in 1968 has resulted in widespread damage to vegetation and soils and a dramatic increase in associated soil erosion. Although the unique water resources of the Inland Delta of the Niger River have helped to buffer the area against the drought, changes are occurring in this area which have their source in the continued lack of rainfall in the Sahel.

As a means of addressing the complex evolution of landforms in this area, digital Landsat MSS data acquired in 1976 and 1984 were analyzed and used as a base for mapping landforms and soils of the upper Inland Niger Delta (Fig. 2). These data, used in conjunction with field mapping and sampling, provide a basis for assessing changes in this field area that are related to continuing morphological processes as well as drought-related trends.

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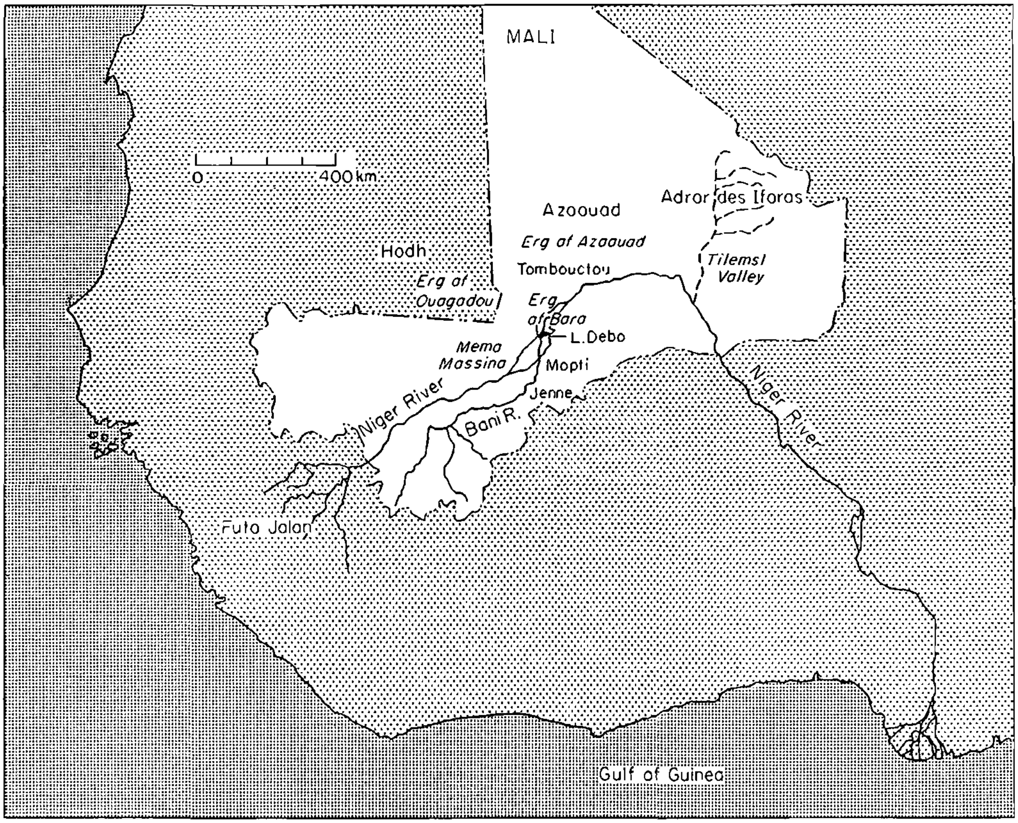


Figure 1. Sketch map of West Africa showing the course of the Niger River and the location of major features discussed in the text.

Previous studies

Several authors have provided extensive reviews of prior work in the Sahel. Notably, a thorough discussion of Quaternary studies pre-1968 is provided by Grove & Warren (1968), while Talbot (1980) provides an extensive synthesis of studies of Quaternary Sahelian paleoclimate through 1980. More recently, a summary review of work on the morphology and climatic history of sub-Saharan West Africa and the Inland Niger Delta specifically was published by McIntosh (1983).

Numerous studies have been published regarding the Late Quaternary climate of the Sahelian zone, utilizing a diversity of data sources. Grove & Warren (1968) compared landforms and soils across the sub-Saharan margin, and devised a chronology that included a well-marked pluvial at 10,000 to 7,000 y.b.p., with earlier moist phases possibly beginning before 20,000 y.b.p. They recognized several main periods of aridity, the last of which probably occurred in the Mid- to Late-Pleistocene. Landforms younger than 7,000 y.b.p. indicate a recent past that has been generally more humid, with episodes of aridity. Street & Grove (1976) used radiocarbon dating of lake limestone and organic material in conjunction with lake-level data from 58 African basins to formulate a refined chronology showing a widespread, intense period of aridity from 15,000 to 13,000 y.b.p., followed by a shift to moister conditions between 12,500 and 10,000 y.b.p. They suggest that this moist phase is the African counterpart of the late glacial phase in Europe. They document moist conditions over the period 10,000–9,000 y.b.p. with peak high water levels between 9,000 and 8,000 y.b.p., followed by a return to aridity at 7,500–6,000

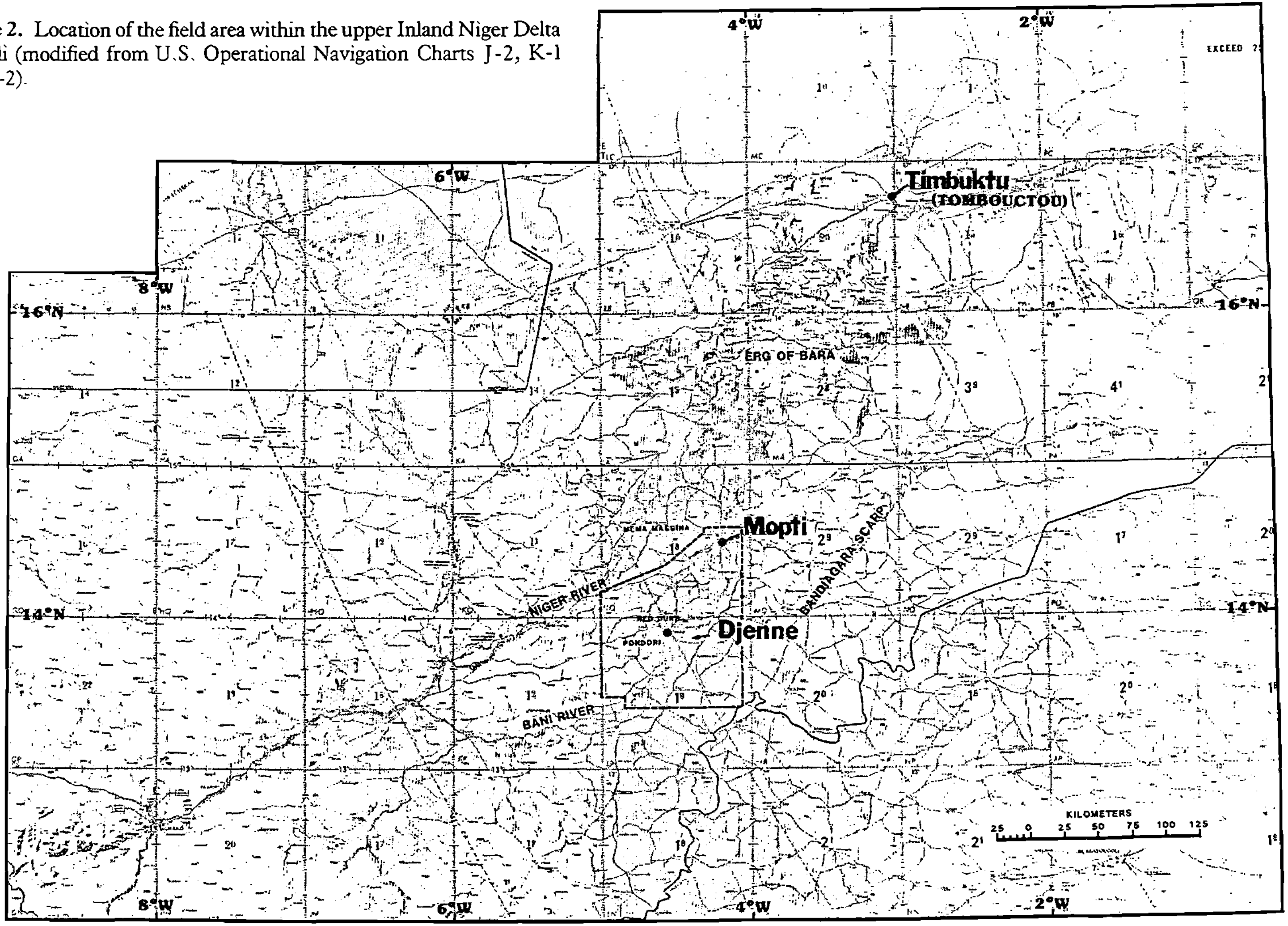


Figure 2. Location of the field area within the upper Inland Niger Delta of Mali (modified from U.S. Operational Navigation Charts J-2, K-1 and K-2).

y.b.p. After noting a modest rise in lake levels between 6,000 and 4,800 y.b.p., these authors note that the succeeding 5 millennia have seen a general reduction in surface water storage, punctuated by periods of greater runoff which were increasingly restricted in extent.

Talbot's (1980) discussion of the available geological evidence for Sahelian climatic reconstruction provides a critical discussion of work published prior to 1980, and reviews the methods and implications of morphological data. On the basis of the reviewed prior work and interpretation of aerial photography and satellite images, Talbot outlines a general paleoenvironmental history marked by three episodes of dune building, provisionally dated at 40,000 y.b.p., 20,000–12,000 y.b.p., and 8,000–6,000 y.b.p., with present-day remobilization of dune sands. Interpretation of the morphologies and stratigraphy of major active and relict watercourses, indicates a more humid, monsoonal phase at 10,000–8,000 y.b.p., followed by periods of aridity and corresponding stream incision from 8,000–7,000 y.b.p. and at 4,000 y.b.p., with generally moist conditions prevailing in the interim.

Historical records have been used in concert with other data to document climatic conditions in the Sudano-Sahelian region over the past 500 years (Nicholson, 1979). Chronicles and other records indicate increased rainfall from the 16th through the 18th centuries A.D., with several severe droughts interspersed. The 19th century in turn was characterized by an early drought episode, followed by humid conditions late in the century. Drought returned in the early 20th century. More humid conditions prevailed in the 1950s and early 1960s prior to onset of the current Sahelian drought.

Complex interactions in atmospheric circulation patterns are implicated as the mechanisms involved in causing the documented climatic changes. Correlations between occurrences of equatorial ocean upwelling, and the position and slope of the intertropical convergence zone (ITCZ), have been documented with reference to reconstruction of the Sahelian climatic chronology (Flohn & Nicholson, 1980).

The studies discussed above are continental in scope and address the morphologies of the Sahel as indicators of past climatic conditions. In addition to these, there have been a number of regional studies specific to the Inland Niger Delta. Studies of the lower Inland Niger Delta near Tombouctou have focussed on the evolution of the Niger River through the Quaternary and Holocene, and have postulated former drainage of the Niger northward past Tombouctou into the Azaouad Depression (Chudeau, 1913; Furon, 1929; Urvoy, 1942; Palausi, 1955; Kervran, 1959; Tricart, 1959, 1965). Chudeau (1913) dated this northward flow to the time of the last European glacial maximum, and suggested the presence of a great shallow lake in the Azaouad. Furon (1929) mapped now-abandoned channels leading north from the Mema Massina (west of the present Inland Niger Delta) to the Hodh Depression. Urvoy (1942) formulated a chronology for the evolution of the entire Inland Niger Delta which began with the Niger River feeding lakes in the Hodh and Azaouad Depressions during the (European) Wurm glaciation. This was followed by a dry phase during which the Ergs of Ouagadou, Bara and Azaouad were formed. Upon a return to more moist conditions, an enormous lake was formed over the upper Inland Niger Delta, which persisted until the Niger was able to breach the Erg of Bara and feed a large lake at Tombouctou. Tricart (1959, 1965) dated the construction of the Ergs of Ouagadou and Azaouad and consequent disruption of drainage to the European Riss, followed by a 'pluvial' period at 100,000–75,000 y.b.p., during which the Niger and Bani Rivers converged to form the Tombouctou lake. He correlated construction of the Erg of Bara and blockage of the Niger drainage system to a dry episode contemporaneous with the pre-Flandrian glaciation, followed by a return to wetter conditions during the Flandrian resulting in the formation of a large lake (Lake paleo-Debo) south of the Erg of Bara and covering much of the upper Inland Niger Delta. Tricart emphasized that recent, rapid subsidence was responsible for the formation of paleo-Debo, and for the anomalous, linear shapes of hills and lakes in the region, as well as the apparently consistent eastward migration of rivers in the region.

Work by Nicholson (1979) and others discussed above and by McIntosh (1983) recasts the dates of events hypothesized by Tricart, but the basic relative chronology proposed by Tricart remains intact. Although the broad framework for the climatic history and morphological evolution of the Inland Niger Delta has thus been established, certain issues regarding the upper Delta in particular remain in question. McIntosh (1983) published a detailed report on field investigations conducted in the upper Inland Niger Delta near Jenne, and suggested in particular that the existence and/or extent of Lake paleo-Debo be re-examined, along with the concept of rapid subsidence as a driving force behind formation of the lake and migration of river channels in the Inland Niger Delta. Recent field work and study of digital satellite image data for the upper Delta (by the present author) also suggest that some aeolian features within the upper Delta are younger than has been thought. This paper represents an attempt to address the geomorphology of the upper Inland Niger Delta, to describe the processes presently operating there, and to extend the work already begun.

Geological setting

The Niger River, which rises in the Futa Jalon highlands of Guinea, flows northeast across the folded Precambrian schists of the Man Shield which are exposed across much of southwest Mali (Black & Fabre, 1983). At approximately 13°20′N lat., 6°30′W long., the Niger crosses onto a discontinuous sequence of clastic sedimentary rocks ranging in age from Proterozoic to Pliocene. Overlying this sequence are the sediments of the Inland Niger Delta, the morphological expression of which is a vast silt-covered plain of very low gradient, with an average elevation change of less than 6 cm/km northward across the Delta area (Furon, 1963). The combination of reduced gradient and underlying sediments results in an abrupt change in the morphology of the Niger River, from a moderate to low sinuosity single channel, to a complex braid of channels flowing through the annually inundated floodplain of the upper Delta. The Bani River, which rises in the Precambrian Toun Schists in the south of Mali, runs roughly parallel to the Niger across these heavily dissected highlands and converges with the Niger at Mopti. Above the confluence, the Bani exhibits low sinuosity with obvious meander scars in upper tributaries and near its source, and a low sinuosity channel near the confluence. The entire inundated floodplain is characterized by intricate Niger–Bani distributary channel systems, with a complex history of incision, aggradation and abandonment. This distributary network gives a surficial pseudodeltaic morphology to the area.

The southern boundary of the upper Inland Niger Delta is formed by highlands carved from heavily dissected Precambrian schists. To the east, the Delta is bounded by the Bandiagara Scarp, which is the edge of a westward-dipping plateau of fractured, dissected Bandiagara Sandstone. To the west lies the Mema Massina or Dead Delta, an inactive distributary system morphologically similar to the currently active upper Delta, but now invaded by dune sands. Finally, the upper Inland Niger Delta is bounded on the north by Lake Debo which is, at least in part, a result of the damming of the Niger by the dunes of the Erg of Bara. The Niger anastomoses into a number of finer channels to penetrate the dune system, and re-emerges north of the Erg of Bara as a single, heavily braided channel flowing northeast past Tombouctou, along the southern margin of the Azaouad Depression (Fig. 3).

Within the upper portion of the Delta, the specific region under study extends northward from the shallow, fertile Pondori basin to the point at which the Mayo Dembe distributary diverges from the Niger River. The study area is delimited on the east by the Bandiagara Scarp, and on the west by the Niger River and a line at approximately 4°50′W longitude. The two major towns within the area are Jenne (13°55′N, 4°31′W) and Mopti (14°29′N, 4°10′W).

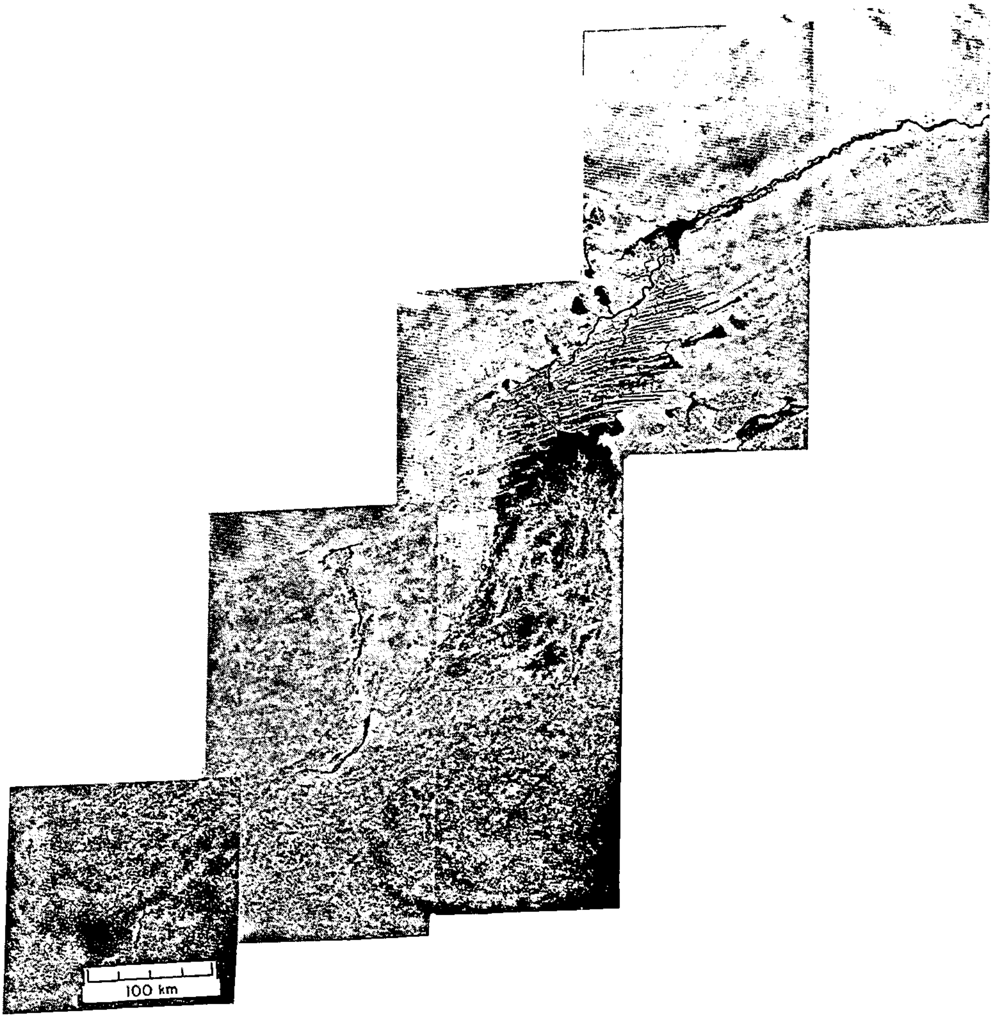


Figure 3. Mosaic of Landsat frames over the Inland Niger Delta. The Niger River flows northward past Mopti, where it is joined by the Bani River. The town of Jenne and the agricultural Pondori region are shown just south of a major linear dune discussed in the text. Distributary channels of the Niger and Bani give a distinctive deltaic appearance to the field area. North of the field area, the Niger breaches linear dunes belonging to the Erg of Bara.

Climate and vegetation

Although the study region is part of the Sahel, the Inland Niger Delta and its annual inundation zone are sufficiently large to effect local modifications of the regional climate. Specifically, for a given latitude, temperature extrema are moderated by several degrees within the Delta. The increased availability of surface moisture during part of the year also results in local conditions of higher relative humidity as well as increased vegetation cover (Kamaté, 1980).

The dominant natural vegetation covering the inundated floodplain is a combination of several species of tall grasses, collectively termed the *bourgou* vegetation. Rice is cultivated in those areas of the floodplain with appropriate rainy-season water depths (1–2 m), and millet is grown in the southern portion of the field area as well as on selected slopes in the northwest quarter. Acacia is abundant; however, large trees are uncommon and are usually found on occupation sites, although baobab are found on generally lateritized soils developed upon the well-sorted, friable Koutiala Sandstone which borders the study area on the east. The more resistant and highly variable Bandiagara Sandstone forms low hills and outliers of the Bandiagara Scarp.

The year 1965 marked the first appearance in the field area of the current Sahelian drought, with a reduction in rainfall as great as 30% as compared with a mean calculated against the preceding years during which records were kept. By 1973 the situation had attracted world attention, with conditions deteriorating progressively through 1974. Three years of improved rainfall (1976, 1978 and 1979) led some authorities to believe that the drought had ended. However, the rains failed again in 1980 and conditions deteriorated until 1985. As a result, the linked processes of vegetation failure, remobilization of previously stable aeolian deposits and active erosion of soil have become endemic.

Method of investigation

This study consisted of three phases: (i) analysis of Landsat images in digital format for the study area, acquired in February 1976 (during the dry season) and August 1984 (during the rainy season); (ii) statistical analysis, visual interpretation and preliminary mapping based on these data followed by 5 weeks of field study, including morphological mapping and sampling of major surface units; and (iii) synthesis of remotely sensed information and interpretations with field evidence, supported by appropriate laboratory examinations of materials sampled.

Remote sensing methods

Remote sensing data analyzed were digital Landsat multispectral scanner (MSS) data. The two images used most extensively for mapping and assessment of vegetation and soils were acquired on 7 February 1976 by Landsat 2 (during the dry season) and on 6 August 1984 by Landsat 5 (during the wet season). The dry season coverage is most useful for thematic mapping of soils, lithologies and landforms, while the wet season image provides supplementary information about vegetation, cultivation and, incidentally, relative topography (since certain low-lying areas are inundated at this time).

The initial processing step for any use of the digital Landsat data is a procedure to destripe the data. Faint horizontal stripes are visible in many Landsat images, and are due to a slight miscalibration among detectors onboard the satellite. In spite of preprocessing carried out before the data are made available on tape, this striping remains and is a source of noise which interferes with subsequent statistical analysis and visual interpretation. Several procedures exist to compensate for Landsat's six-line striping (Siegal & Gillespie, 1980). The method used to correct the data in this study involved the use of a table of additive correction factors which, when applied to striped data, serve to normalize the response of each detector to a common mean. The net result is a significant reduction in striping in the final images, with a corresponding increase in usefulness and interpretability.

Following the radiometric de-striping correction, digital data were subjected to statistical analysis and image enhancement. The simplest method consisted of developing a colour image from three of the four spectral band images which comprise each scene, by encoding the three separate images representing the wavelengths or spectral regions 0·5–0·6, 0·6–0·7 and 0·8–1·1 μm, respectively, as the blue, green and red components of a single composite image. This yields a standard false-colour composite in which vegetation appears in shades of red. Computer colour images thus obtained were used to map major landforms and soils and to distinguish first-order seasonal changes.

Additionally, all channels of both images (a total of eight) were treated as variables of a single eight-dimensional dataset, and were transformed using principal components analysis. In this method, corrected, 'de-striped' digital data files containing image information from both the wet and dry season scenes, were registered to the same map projection using UTM grid reference points determined from maps at the scale of 1:1,000,000. Although the scale of the base maps undoubtedly led to slight inaccuracies in the image latitude and longitude coordinates of any given feature, the registration between the two scenes was precise. Therefore, the analysis remained valid.

Following the co-registration procedure, all data were subjected to statistical analysis using the principal components rotation (Byrne, Crapper *et al.*, 1980; Richardson, 1982). The effect of a principal components transformation is to optimize the availability of information (i.e. variance) in the dataset, by combining redundant information and isolating subsidiary trends within the data. Multispectral satellite image data are generally highly correlated, due to the dominance of panchromatic brightness in controlling the appearance of a given image. In visual interpretation, subtle colour differences can be obscured by the strong effect of albedo. Principal components analysis serves as a means of identifying correlated, panchromatic information and separating it from minor (but potentially important) colour trends.

In effect, application of this technique to two multispectral Landsat scenes whose acquisition is separated by a given time span, yields a sequence of transformed images which contain progressively less correlated information. The first principal component image, containing the highest percentage of correlated information, is essentially an albedo image which illustrates broad-scale brightness patterns and landforms present during satellite acquisition of both Landsat scenes. The remaining images emphasize areas of uncorrelated data and may be used to isolate differences between the two images. Figure 4 shows the second principal component image from the 1976–84 analysis, which contains the most information about colour differences related to documented surface change. Tables 1–3 list the eigenvectors and other statistics resulting from this analysis. It can be seen from the sign reversal across the second component that this image essentially documents broad-scale colour and brightness changes. Areas of apparent brightness change were targeted for field inspection and further remote sensing analysis. Significantly, areas along river and stream channels consistently showed the greatest albedo increase.

Field study

A 5-week field investigation of the study area was conducted during January and February 1985, during which a network of foot and vehicle traverses were taken over the study area. The purpose of the field work was to document soil and vegetation associations and to verify map units and interpretations based on the remotely sensed information. Representative samples were obtained for major surface units and estimates were taken of the density, as well as type, of vegetative cover. The condition of surface materials (disturbed

Table 1. *Channel statistics*

	1976				1984			
Channel	1	2	3	4	5	6	7	8
Mean	25·75	36·25	42·82	36·96	52·02	68·28	68·08	60·11
SD	4·19	8·07	7·66	7·04	4·23	6·91	7·09	6·27
Coefficient of variation	0·16	0·22	0·18	0·19	0·08	0·10	0·10	0·10

Table 2. *Covariance matrix*

17·57							
31·75	65·19						
26·78	55·94	58·68					
19·92	43·02	49·58	49·53				
6·70	10·61	8·85	6·57	17·93			
13·17	24·41	20·22	14·28	26·36	47·70		
14·10	29·08	25·19	17·82	19·31	38·38	50·28	
10·55	22·58	20·54	15·40	13·56	27·75	41·89	39·36

Table 3. *Principal component statistics*

		Component							
Channel		1	2	3	4	5	6	7	8
1976	1	0·057	–0·031	0·033	–0·086	0·101	–0·008	–0·058	0·175
	2	0·060	–0·036	0·012	–0·073	–0·007	0·042	0·016	–0·053
	3	0·060	–0·047	–0·004	0·020	–0·032	–0·098	0·016	0·002
	4	0·053	–0·052	–0·010	0·095	0·021	0·068	–0·020	0·007
1984	5	0·038	0·065	0·105	0·037	0·154	–0·058	–0·018	–0·101
	6	0·047	0·066	0·082	0·019	–0·061	0·024	0·037	0·039
	7	0·052	0·065	–0·048	–0·008	–0·029	–0·005	–0·098	–0·016
	8	0·048	0·060	–0·091	0·001	0·048	0·004	0·093	0·016
Variance by component (%)		64·42	22·61	6·47	4·43	0·76	0·55	0·41	0·35
Cumulative variance (%)		64·42	87·03	93·50	97·93	98·69	99·24	99·65	100·00

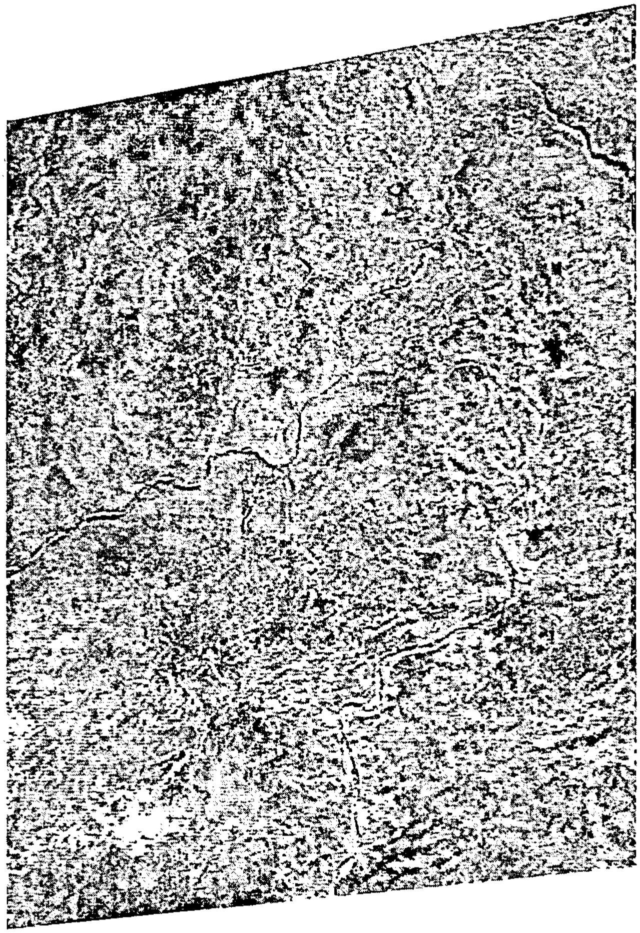


Figure 4. Image of the second component from an eight-channel principal components analysis showing areas of significant change. Bright portions of this image correspond to areas of net albedo increase. Such areas were found to have indications of vegetation and soil damage in the field, and are consistently associated with levee deposits along stream channels.

or undisturbed) was also noted. Where active erosional processes were observed, an attempt was made to document the dominant agent (wind, water or both), and to estimate the areal extent and severity of the erosion.

In addition, a separate hydrological survey of the area was conducted by the author's field assistant. Water level and quality were measured in over 40 wells across the field area. These measurements and others were compared later with well records kept by the Division of Hydrology in Bamako.

Following the field work, supplementary remote sensing analysis was conducted to refine earlier thematic maps through addition of field data. Petrographical analyses were conducted for sediment samples representing major surface units prior to preparation of maps and interpretations.

Results

Major landforms and soils

Figure 5 presents a preliminary geomorphological map of the field area, based on both remote sensing analyses and field work. Where possible, the map also presents information related to vegetation. The channels and joint floodplain of the Niger and Bani Rivers are the major geomorphic feature of the area. The two rivers operate under different dynamic systems despite their proximity and, as a result, they have distinctly different morphological characteristics. Within the field area, the Niger channel is low to moderately sinuous with an abundance of sandy point bars and beach deposits. Previously, the Niger showed a stronger tendency to meander, as is evidenced by the distinct meander scars along either side of the present Niger River channel. Evidence is minimal for the main channel of the Niger having meandered more than a few kilometres southeast of its present position.

The smaller Bani River has changed course a number of times. The upper Bani River channel is heavily braided, although currently the channel appears to be incising and developing single-channel morphology. This river carries a substantial bedload of poorly sorted material obtained from tributaries eroding the Koutiala and Bandiagara Sandstones to the east.

Much of the field area is characterized by the presence of a network of channels distributary to the Bani and Niger Rivers. Several major distributary channels, which represent former courses of the Bani and former confluences of the Bani with the Niger, transect the wedge of land between the Bani and Niger north of Jenne. These aggraded channels still carry water for part of the year. East of the three major paleochannels is the Femaye, an area of deep, actively incising channels and high natural levees of the Bani. High levee deposits also exist along the Bani south (upstream) of Jenne. These levees are composed primarily of silt and clay, with depressed backswamp areas and associated sandy beach deposits which are reworked and winnowed by the dry season winds, with additional fluvial modification during the wet season.

The western portion of the field area (northwest of Jenne and south of the Niger River) exhibits a complex system of small channels, some of which carry water following the wet season. These fine relict channels may represent former courses of the Bani or Niger, and are discussed in detail below.

Soils are quite uniform over much of the depressed, nearly level floodplain. Between Mopti and Jenne these soils consist of a sequence of homogeneous laminated silts which, in many locations, show evidence of extensive fluvial reworking. These silts have a very low organic content and show essentially no soil profile in most locations visited. However, the silts northwest of Mopti show some evidence of development of a semi-consolidated silica-rich duricrust. These extensive silt deposits represent the essentially depositional environment of the inundated floodplain during the wet season. Fluvial reworking of the sediment column occurs over the multi year timescale; however, yearly aeolian redistribution of surficial layers is common, especially in areas in which the consolidated dried silt surface is disrupted. Regional variations in silt colour and texture are minor, with a few notable exceptions such as the Pondori area south of Jenne (discussed later). Some colour variations on the scale of a few metres are due to the presence of thin deposits (commonly only a monolayer of large, reddish grains) of fluvially derived sands now being modified and transported by wind.

Superimposed on the silts of the western portion of the field area are a few small linear dunes of the order of a few metres in height, with numerous, poorly defined sand stringers less than one metre in height. These features are oriented northeast–southwest and are composed of clear to yellow fine sands. Agriculture is practised on some of these dunes, although no definitive evidence of stabilization was found. In fact, the small scale and mobility of these dunes argue for a modern origin, and field measurements of aeolian

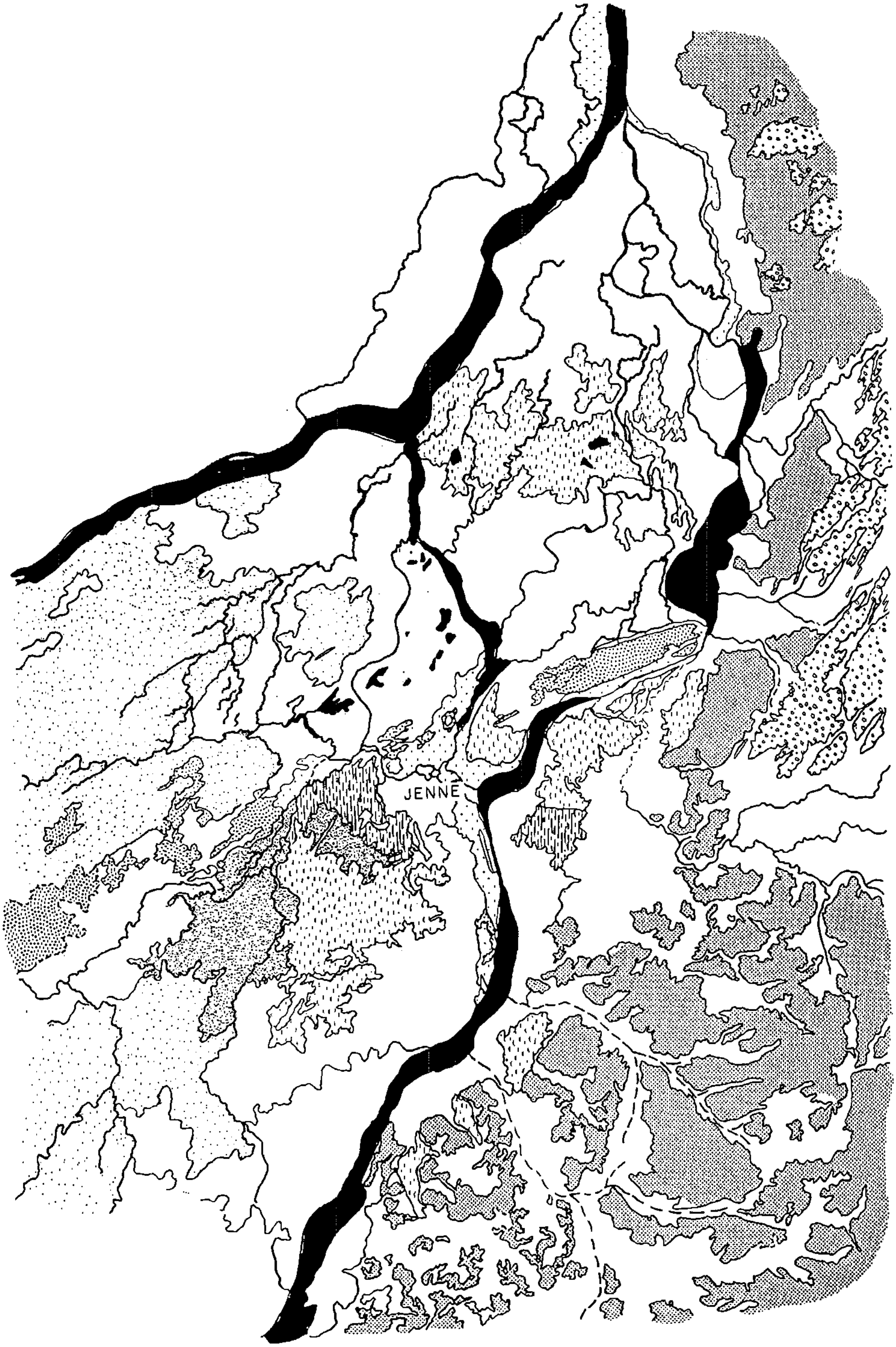


Figure 5. Geomorphological map of the field area. Major soil units and landforms are discussed in the text. Features were mapped on the basis of satellite data analysis of soil colour, brightness and associated vegetation patterns, and were field checked for accuracy (see facing page for key).

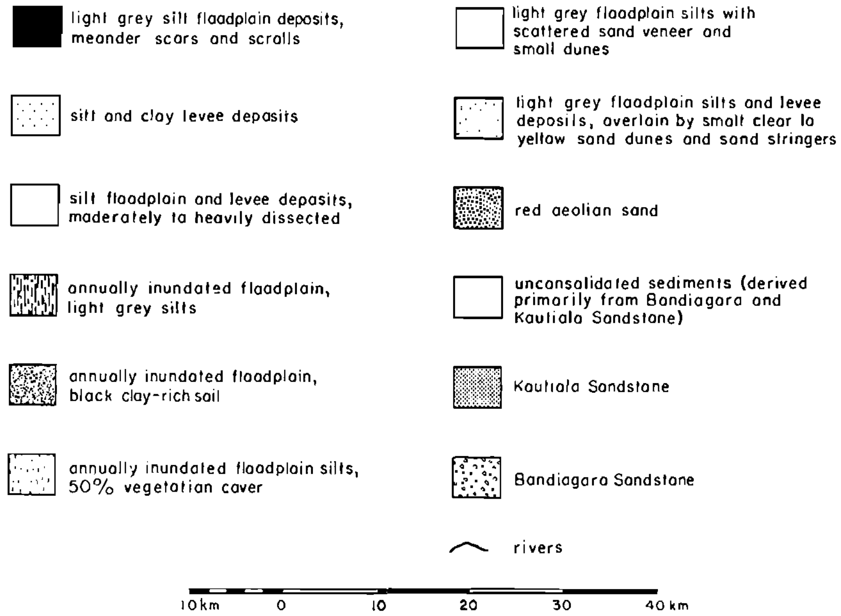
transport directions support this hypothesis. The dunes are veneered with a mobile lag of slightly coarser, reddish quartz sandgrains similar to those described above, and which probably represent the coarser fraction of fluvial sediment transported during the flood season and subsequently reworked by wind. These dunes may represent contemporary redistribution of the sand-sized fraction of sediments transported into the area by floodwaters and as stream bedload during the wet season. Further field work and sampling during the wet season are needed before this hypothesis can be evaluated fully.

One massive linear dune composed of distinctive red sand crosses the field area southwest to northeast just north of Jenne. Although the dune is only a few metres in height, it is more than 80 km long. The eastern limits of the dune are well defined, with evident fluvial bevelling at the dune margin. The morphology becomes less distinct westward, and the dune merges with sheet sands at its western end. The dune has been breached by fluvial channels near Jenne.

South of Jenne and east of the Bani lies the unusual Pondori region, a shallow depression of approximately 150 square kilometres, which is characterized by distinctive, black silt and clay soil. Undisturbed soil sections show fine laminations and a deficit of coarse materials similar to silts elsewhere in the field area. Silts along the shallow fringe of the Pondori resemble the light grey silts ubiquitous to the field area.

Dominant geomorphological processes

Although the upper Inland Niger Delta is currently subject to increased aeolian activity, as a result of recent Sahelian drought conditions, the dominant processes responsible for observed morphologies and modifications to the landforms are, nevertheless, fluvial. The controlling landform of the region is the broad floodplain of the Niger and Bani Rivers. This feature is, as mentioned before, the result of a long history of annual inundation and decantation of fluvially transported silts, with associated reworking of the sediments by migrating, meandering and incising channels responding to yearly varying conditions of



precipitation and runoff. There is evidence, as discussed in brief by McIntosh (1983), that the Bani River formerly occupied the now-senescent Sine Oualo channel to the north of, and parallel to, the Bani's present course (Fig. 6). The relatively fresh morphology of this channel may indicate rather recent abandonment, or may simply indicate continued, present use as a distributary channel. During its use of the Sine Oualo, the Bani successively occupied and abandoned both the Konguene and Mayo Manga channels which join the Sine Oualo with the Niger at Koukourou. Subsidiary confluences of the Niger and Konguene exist at Koa and Kolenze. These minor spurs of the Konguene probably pre-date the confluence at Kouakourou, and are consistent with an eastward-migrating pattern of incision, aggradation and abandonment of successive channels.

As a result of normal aggradation along the Mayo Manga, it appears that the upper course of the Bani River underwent a similar, perhaps rapid, eastward migration. The Sine Oualo was abandoned and the upper Bani River assumed essentially its present position. It is likely that the Souman Bani was formed at this time, in response to the migration of the upper channel. The morphology of the Souman Bani indicates that the direction of maximum gradient still favoured confluence at Kouakourou, although the Mayo Marou, a mature meandering channel and major distributary of the Souman Bani between Lanaoue and Toumaye, may pre-date the confluence at Kouakourou. If so, this points to a subsequent capture of the Souman Bani by the relict, lower course of the Mayo Manga, now shared with the Souman Bani. The implication of such a history is a sequence of evolution for the Bani River in which maturity, aggradation and senescence of channels proceed in parallel with incision of and migration to new channels, in contrast with a simpler model of sequential migration. This model is consistent with the maturity and morphology of the Konguene, Mayo Manga and Souman Bani channels observed by the present author both in the field and on Landsat images and noted by McIntosh (1983), and does not require the rapid subsidence suggested by Tricart (1965) as a controlling mechanism.

The current channel of the Bani River in the southern portion of the field area is moderately braided as far north as Nienou. North of Nienou, one low-sinuosity channel becomes dominant. From a point east of the Pondori northward to Sofara, the channel is remarkably youthful and diverges westward from the Bandiagara Scarp, with the type of long, straight reaches commonly associated with structural control. Although structural control of the Bani cannot be discounted with the evidence now available, aggradation also explains the observed morphology satisfactorily. Just east of the anomalous portion of the Bani channel, a large tributary stream system descends from the Bandiagara highlands (see Figs 4, 5). This stream dissects rocks of the Bandiagara and Koutiala Sandstones, and provides an ample influx of poorly sorted sediments. The sediment supplied by this tributary system may be sufficient to form a topographical barrier along the reduced-gradient floodplain margin, thus forcing the Bani westward at this point. Similarly, aggradation of channels to the west of the Bani (as discussed previously), combined with aeolian reworking of fluvial sands, forces the Bani to resume its eastward migration downstream of the barrier.

The history of the Niger River within the study area has been simpler. The Niger has migrated eastward through time, as evidenced by the presence of several major distributaries which may represent former courses of the river. Within the study area, however, the Niger's primary morphological contribution has been as a source of the silts and coarser sediments which are decanted into the Delta during the annual flood of the Niger. The Niger River itself traverses the northwest portion of the field area. The sinuosity of the main channel is rather low (1·2), and obvious meander scars are seen no farther than 5 km either side of the present channel. The channel is lined with point bar deposits and the river is currently underfit, as a consequence of the recent prolonged drought. Beaches and bar deposits formerly exposed only during the low water levels of the dry season were clearly visible in satellite data obtained during the wet season of August 1984.

Evidence for recent aeolian activity in the field area is abundant. As mentioned before, thin stringers of fine sand veneer the silt plain materials over much of the floodplain between the Niger and Bani. Thicker sand deposits and small linear dunes cover the western portion of the field area, and the area just north of Jenne is dominated by one very large, very red longitudinal dune.

The distinctive morphology, great size and anomalous redness of this dune relative to others in the vicinity have suggested to other authors that this dune is very old (between 20,000 and 12,500 y.b.p.) and that it may be contemporaneous with the larger, massive Erg of Bara dunefield north of Lake Debo (McIntosh, 1983). Distinct redness of dune

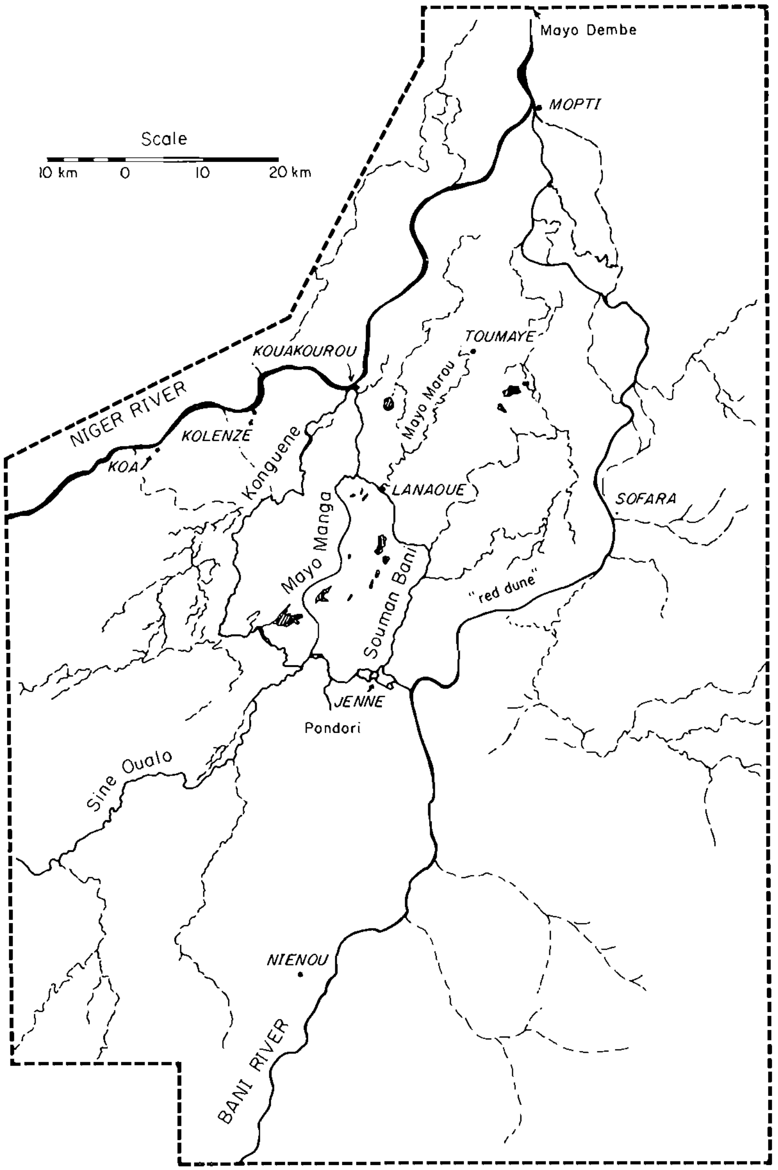


Figure 6. Sketch map of distributary channels within the field area. Many of these channels represent former courses of the Bani River, a major tributary of the Niger.

sand is a classic indicator of age (Norris, 1969; Walker, 1979), but massive longitudinal dunes are usually formed as part of well-ordered dune systems rather than as isolated constructions (Breed and Grow, 1979).

Little field evidence of natural stabilization was found on this dune although the crest is in agricultural use, and the question of former stabilization remains open. However, the sands sampled from this dune are texturally less mature than other aeolian deposits in the region and they are petrologically similar to sands obtained from beach deposits in the Bani River. Analysis of multispectral satellite data also reveals that the spectral characteristics of this dune are essentially identical to those of sediment mantling the eastern border of the field area and derived from the Koutiala and Bandiagara Sandstones. Microscope examination of these sediments for quartz derived from both the dune and sandstones indicates similar textural properties and colour. The sands sampled at the large red dune may be the relatively recent result of short-distance aeolian transport of Koutiala–Bandiagara sediments.

The distinctive longitudinal morphology of this dune is, in this case, not likely to be the sole remnant of past formation of a large well-ordered dune cordon, but is rather the result of favourable sedimentological and topographical conditions. In addition to the abundant sediment supply upwind of the area of deposition, there exists a narrow defile in the Bandiagara Scarp upwind of the sediment source region, as noticed in Skylab photography (McIntosh, 1983). This configuration is likely to result in an associated high-energy Venturi regime favouring sand transport. The age of the dune remains in question, in view of the lack of evidence for subsurface consolidation. The current surface transport observed on this feature may reflect remobilization of an old feature as a function of intensive agricultural use and the Sahelian drought, or may be simply a reflection of equilibrium between sand supply and sand transport on a relatively modern feature.

Analysis of drought damage and documentation of changes in soils and vegetation due to prevailing dry conditions are still in progress. Preliminary results indicate that over 75% of lakes, ponds and swamps mapped as permanent waterbodies in the 1950s, and which carried water through the dry season as late as 1976, are now ephemeral. Most of these waterbodies were visited during the January and February 1985 field work, and were completely dry. Formerly permanent watercourses distributary to the Bani and Niger were also found to be dry. These stream courses are now incised, and floodplain soils show evidence of recent sapping, which may be related to documented lowering of the water table in response to continued groundwater withdrawal. Comparison of the 1976 and 1984 Landsat data indicates a reduction in vegetation and diminished areas of cultivated land.

Over the study area and the entire region of the upper Delta, significant increases in albedo and associated changes in colour due to soil damage were verified in the field. Damaged areas show as characteristically very high albedo. In the field, these high-albedo areas were observed to have less than 10% vegetation cover, strongly disrupted soils with disaggregation and lowered cohesion of soil particles, and a strong component of aeolian transport.

Satellite data also show that both the Bani and Niger Rivers are more turbid at present than they were in the early and mid-1970s, which is consistent with an increase in sediment yield from devegetated and soil-damaged areas within the local environment. Also apparent from analyses of the two Landsat scenes, is that less water was contained in the Niger and Bani Rivers during the rainy season of 1984 than was carried during the dry season of 1976.

Conclusions

The morphology of the upper Inland Niger Delta is largely the result of fluvial processes of the Niger and Bani Rivers, with aeolian processes and landforms superimposed. Both rivers operate within a framework of eastward migration across the Delta, but the two rivers have distinct morphologies. The Niger is a low to moderately sinuous single channel, with abundant point bars and beaches; distinct meander scars appear on either side of the present channel, but evidence for migration outside of these rather narrow limits either does not exist, has been obscured, or is below the resolution of the Landsat MSS system. In contrast to the Niger, the channel of the Bani River is heavily braided, although at present there appears to be a tendency toward incision and development of a single sinuous channel. The Bani has migrated actively, and many of the Niger–Bani distributary channels are former courses of the Bani. Morphological evidence suggests that the observed migration of the Bani may be largely a function of abundant sediment supply relative to the river's competence, thus causing continual incision, aggradation and abandonment of channels through time. Rapid subsidence and/or structural control in the upper Inland Niger Delta, as a mechanism for channel migration, can neither be confirmed nor ruled out on the available evidence, and this topic awaits further study.

The joint Niger–Bani floodplain, upon which these distributaries are developed, is characterized by distinct natural levees and uniform, light-grey floodplain silts with little or no soil profile development. Some soils are laminated, but reworking is extensive and the typical vertical section is homogeneous. A sparse, mobile veneer of poorly sorted reddish sand covers these silts over much of the delta. Aeolian redistribution of these sands is common. Small dunes are found in many portions of the upper Inland Niger Delta and cover much of the northwest quarter of the field area. These dunes have been considered to be related to the Erg of Ouagadou to the north, but field evidence and examination of satellite data indicate a more recent origin. Similarly, the linear dune north of Jenne, although massive and exhibiting the red colour considered typical of old, stabilized dunes, may be a relatively recent feature in equilibrium with the current sediment supply and wind regime. Further field work during the wet season, including extensive sampling, trenching and wind measurement, is needed before the age of these features can be better defined.

Changes over the past 8 years have been observed in the field area and the upper Inland Niger Delta in general, using satellite data in conjunction with field observation. Preliminary results indicate that the changes observed are related to drought conditions in the Sahel. Over 75% of lakes and watercourses mapped as permanent during the 1950s were dry during field visits in 1985. Evidence of sapping was observed in floodplain soils in the area. Comparison of 1976 and 1984 satellite data showed a marked decrease in vegetation cover and a corresponding increase in exposed soils and areas with soil damage. Despite the fact that the 1976 data were acquired during the dry season and the 1984 data were acquired during the wet season, when vegetation and soil moisture should have been maximized, a net albedo increase in excess of 15% was calculated for portions of the study area. These observed shifts in the dominant morphological processes in the study area, and other indications of drought damage in the upper Inland Niger Delta, are the subject of current continued investigation.

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