Application of Landsat Products in Range- and Water-Management Problems in the Sahelian Zone of Mali, Upper Volta, and Niger

Prepared on behalf of the Office of Science and Technology, Agency for International Development, U.S. Department of State

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1058

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By M. E. COOLEY *and* R. M. TURNER

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Landsat imagery can aid in solving problems related to natural phenomena and human activity

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Application of Landsat Products in Range- and Water-Management Problems in the Sahelian Zone of Mali, Upper Volta, and Niger

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ABSTRACT

A brief field investigation during April and May 1974 to evaluate the application of Landsat (formerly ERTS) imagery to range- and water-management problems in Mali, Upper Volta, and Niger shows that imagery can provide general overviews of regions or even entire countries, can be used in areas where few or no good ground surveys exist, can provide a basis for repetitive inventorying and monitoring transient environmental changes on the Earth's surface, and can aid in solving special problems of disease-vector control or human activity. Specific potential applications of Landsat imagery were identified in river-blindness control, tse-tse fly control, bush-burning evaluation, distinction of arable from nonarable lands, analysis of problems of accelerated erosion, and monitoring of the annual flood of the Niger River, and of ground-water development in fractured rocks.

Introduction

As increasing pressures from drought, overgrazing, and human population have developed in West Africa, especially in the Sahelian countries (Dalby and Church, 1973; Wade, 1974; Sterling, 1974), the need for repetitive inventory and surveillance of natural resources is becoming more critical. Landsat imagery provides a valuable tool for detecting, evaluating, and cataloging fixed Earth-resources information as well as for monitoring transient seasonal changes in the environment. Because of the large area (34,000 square kilometers) encompassed by each frame, Landsat imagery is well suited for obtaining a general overview of a region and is helpful in solving certain problems not requiring large-scale imagery. Landsat capability to view the Earth simultaneously and repetitively in four spectral bands chosen to emphasize water and land resources is further reason for anticipating that this satellite can yield valuable information for managing the resources of the Sahelian region south of the Sahara in West and Central Africa and of other comparable arid regions of the world. Because the data-recording instrument aboard Landsat 1 had ceased operating, images of Africa were not recorded for several months before June 1974. Nevertheless, imagery recorded during 1972 and 1973 proved to be entirely adequate for the objectives of the present work. Landsat 2, however, was launched in January 1975. This satellite could be employed to continue studies such as those undertaken in this project.

In the short time since Landsat 1 was placed in orbit in July 1972, considerable interest has been directed to using imagery from the satellite to study the Sahelian region lying to the south of the Sahara in West and Central Africa. The Office of Science and Technology of the Agency for International Development (AID), U.S. Department of State, began a program in 1973 to determine the utility of Landsat products in resource-management problems of the Sahel. In February 1973, Maurice Grolier, U.S. Geological Survey, visited Mali, Niger, the Ivory Coast, Senegal, and Mauritania to make preliminary arrangements for a regional remote-sensing workshop planned by AID for later that year. The workshop was held in Bamako, Mali, during April 1973 (Grolier and others, 1974). That same spring, AID sponsored a Landsat-oriented demographic study in Upper Volta and Niger (Reining, 1973). In addition, the National Aeronautics and Space Administration has supported at least two Landsat investigations of the Sahelian region; N. H. MacLeod, American University, has been studying plant growth and annual flooding in the Niger River, and the Republic of Mali has been conducting natural-resources investigations using Landsat imagery. Also under AID sponsorship, a two-man team of Landsat specialists (Jones and Miller, 1974) made a visit during September and October 1973 to assess the possibilities of expanding and strengthening Landsat applications programs in the three Liptako-Gourma Authority (LGA)[1] countries of Mali, Upper Volta, and Niger (fig. 1). The present investigation is an outgrowth of this visit and of additional planning sessions between African and U.S. officials.

As a continuation of its program for furthering the utilization of Landsat products in this study

[1]The LGA (more fully, Authority for Integrated Development of the Region of Liptako-Gourma) has the objective of promoting the development of minerals, energy, water, agriculture, livestock, and fish culture in Mali, Niger, and Upper Volta in the region near the Niger River known as Liptako-Gourma (fig. 1).

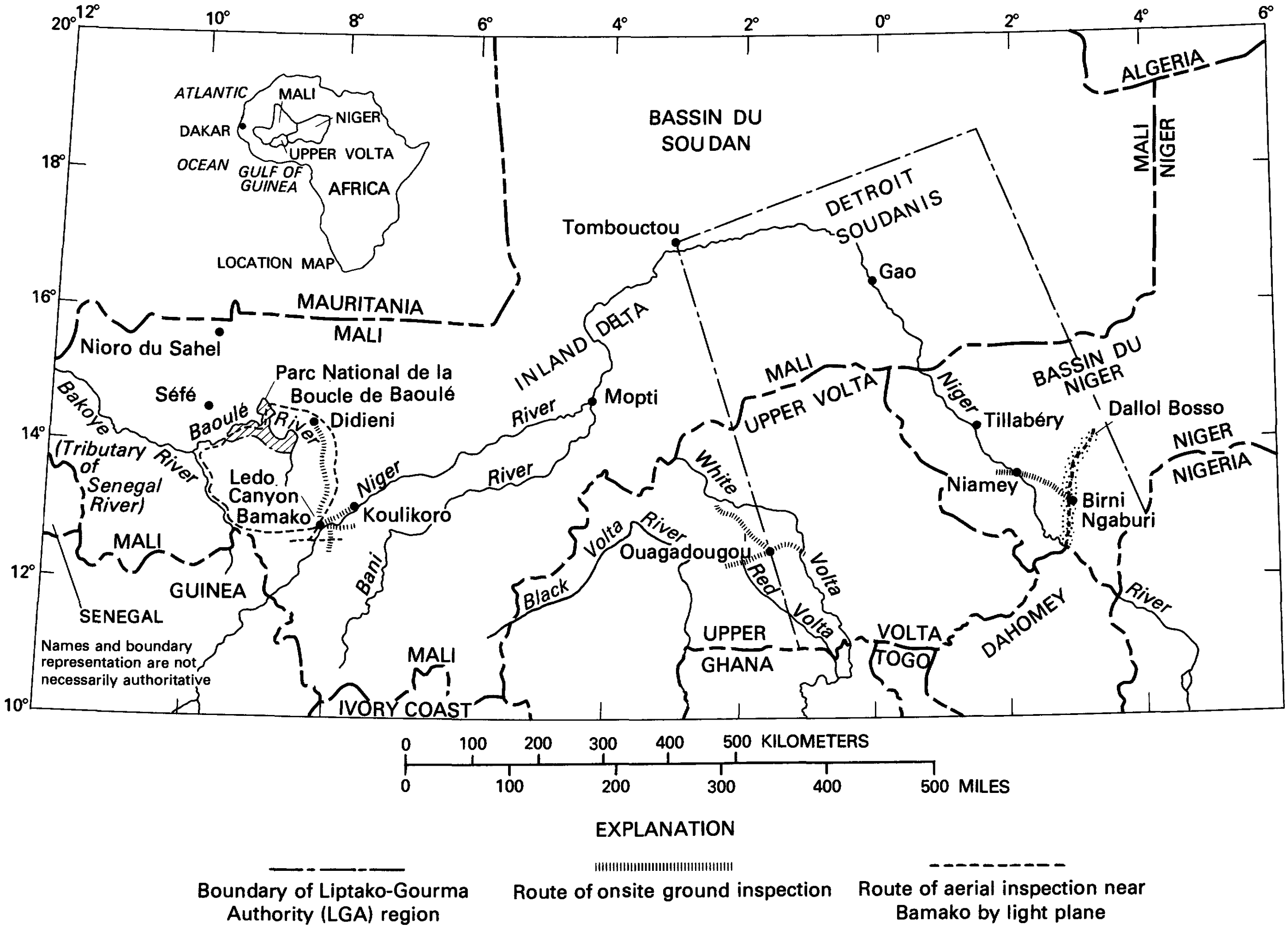


FIGURE 1.—Map of the Liptako-Gourma Authority region and adjacent areas in Mali, Niger, and Upper Volta showing principal physical features and localities visited during onsite inspections.

and evaluation of the natural- and human-resources problems of the Sahel, AID requested the U.S. Geological Survey undertake a project for identification of significant range- and water-management problems that could be studied and evaluated from Landsat imagery. Accordingly, M. E. Cooley, geohydrologist, and R. M. Turner, botanist, both of the Geological Survey, were assigned to Mali, Upper Volta, and Niger from April 12 to May 27, 1974, to carry out the work. The problems evaluated during the writers' fieldwork included those associated with use and development of arable land, bush burning, location of villages and heavily grazed stock trails, tse-tse fly and river-blindness control, extent and duration of inundation by the annual floods of the Niger River, and identification of localities favorable for accumulation and production of ground water. The results are presented in part in a series of illustrations (figs. S-1—S-6) located at the end of this report showing specifically what can be done with the Landsat imagery in evaluating some of these problems.

Acknowledgments

The cooperation of many individuals who willingly gave of their time and knowledge of the regional problems contributed much to the success of the project. Before departing from the United States, the writers met with Norman H. MacLeod, American University, who shared with them the results of his ongoing work with Landsat imagery in West Africa. Charles F. Withington, Geological Survey in Reston, Va., gave freely of his time and office space while the writers were applying enhancement procedures to Landsat imagery of Africa. Many individuals assisted the writers during their stay in Africa with technical aspects of the project. They are grateful for the help given in Bamako in the fields of botany and geohydrology by Abdoulaye Sow, agrostologist with the National Center of Zootechnological Research. Among others in Bamako with whom they conferred were K. J. R. MacLennan and Eric Carver, who shared with them their knowledge of tse-tse fly life cycles in relation to the vegetation and livestock of the area. In Ouagadougou, John Buursink and Phillip Roark, Comité Interafricain d'Études Hydraulique (CIEH), were helpful in arranging meetings with several informed individuals, in providing pertinent publications, and, particularly Buursink, in contributing their knowledge of the area. In addition, the writers conferred with D. A. T. Baldry and Frank Walsh, entomologists with the River-Blindness Control Program; William Morris, Regional Economic Development Service Office, AID, Abijan; Robert Helmhols, CIEH; and Quétian Bognounou, botanist with the Parc Botanique, Centre Voltaïque de la Recherche Scientifique. In Niamey, they conferred with Ian Pattinson, regional officer of the Entente Fund, who gave them valuable information concerning agricultural practices in Niger.

During the writers' stay in the three capital cities, they were briefed and accommodated in numerous ways by the following members of the American Embassy staffs and AID officials who provided amenities and advice that contributed to a successful program: in Bamako, Ambassador Ralph J. McGuire, Vice-Consul David Peashock, Ray Denacourt, and John Garner; in Ouagadougou, Mark Johnson and Don Atwell; and in Niamey, Eugene Chiavaroli, James Hill, and Albert Baron. In addition, Howard B. Helman, American Embassy, Paris, kindly interrupted his schedule at Bamako to confer with the writers and to act as a translator. He also provided the opportunity for one of the writers to fly over an area being examined by tse-tse control specialists. Also in Bamako, Adama Timbo, acting as an interpreter, quickly perceived many of the technical aspects of the work and was able to cope immediately with its complicated terminology and concepts.

To their African colleagues, the writers express special thanks. Many were already greatly overworked and yet they received the writers graciously. To the following, the writers are especially indebted: in Ouagadougou, to Cyr Mathieu Samaké, Director General, LGA, and to Phillipe Kaboré, Chief of the Documentation Center, LGA; and in Bamako, to Aly Dembele, Service de l'Hydraulique, to Sidy Zouboye, National Society for Research and Development of Mining, and to Bakary Touré, Director General Direction Nationale des Mines et de la Géologie.

General procedure

As originally conceived, the project was to rely substantially on contributions from those Africans knowledgeable in the land, water, and demographic problems of the Sahelian region. Africans representing the three Liptako-Gourma countries were to meet with the U.S. Landsat specialists, to examine the imagery, and, through basic photointerpretation techniques, to draw tentative conclusions concerning various features noted on the images. After this preliminary evaluation, onsite examination was to be made of as much terrain as feasible to check earlier interpretations and to refine the investigators' ability to recognize significant terrain features. The writers' contacts with the Africans, however, proved to be limited, and insufficient time was available for setting up suitable joint schedules to examine the imagery or to make onsite investigations. Consequently, the writers proceeded with the Landsat investigation without the level of direct participation by Africans that was originally anticipated.

Onsite investigation

Because of the short-term scope of the project, the areas selected for study were those easily accessible from the larger cities of the region. These cities are served by air passenger service and by good roads. Six main target sites near Bamako, Mopti, Tombouctou, and Gao in Mali, Niamey in Niger, and Ouagadougou in Upper Volta were selected in advance of the writers' departure for Africa, and imagery covering the sites was ordered from the EROS Data Center at Sioux Falls, S. Dak. The main effort was concentrated near the three national capitals and on part of the Inland Delta of the Niger River between Tombouctou and Mopti. Of these localities, field checking was done only near the national capitals, where trips of more than 100 kilometers into the countryside were made in vehicles rented locally (fig. 1). Of necessity in a region of limited accessibility, the areas inspected were along the main highways that lead out from the capital cities.

Additional onsite checking was made from the air by means of light planes and during commercial jet travel. The area west and north of Bamako, including the Baoulé River and Parc National de la Boucle de Baoulé, was inspected at altitudes between 150 and 200 meters above the ground from a light aircraft. Another flight, made in conjunction with an AID tse-tse control project, permitted viewing of an area south and east of Bamako. Also, useful information that aided in interpreting the imagery was obtained from high-altitude jet aircraft in regularly scheduled flights between the national capitals. These included the flight from Dakar to Bamako, two flights between Bamako and Ouagadougou, a flight from Ougadougou to Niamey, a flight upstream along the valley of the Niger River from Niamey to Bamako with stops at Gao, Tombouctou, and Mopti, and the final flight from Ouagadougou northward across the Sahara to Marseilles, France. Visibility was hindered on parts of these flights by the haze which prevails near the end of the dry season and by high clouds that herald the beginning of the rainy season.

Mapping by use of the Landsat imagery was done only at the scale of 1:1,000,000. For further field use, however, scales of 1:500,000 or 1:250,000 are recommended. (The latter scale is the maximum for bulk Landsat imagery.)

Selection of imagery

Selection of imagery was made from computer printouts obtained from the EROS Data Center. Sufficient time was not available before departure from the United States for the writers to visit the Data Center and to make selections directly from its files, although this would have been the preferred procedure. Approximately 30 different scenes were finally selected providing coverage by several frames around each of the six cities in the LGA region. In some instances, the same areas were covered on two successive dates. Such sequential views provided opportunity to evaluate applications of Landsat imagery to seasonal changes on the land surface. Most of the Landsat images used were 9- by 9-inch positive transparencies (scale 1:1,000,000). All four spectral bands were utilized, and, in some instances, scene features were enhanced by using diazochrome overlays where band 4 (0.5–0.6 micron) was reproduced in yellow, band 5 (0.6–0.7 μ) in magenta, and band 7 (0.8–1.1 μ) in cyan. This technique was particularly useful for examining details of the vegetation and for mapping surficial geologic features. Two other types of Landsat data were also employed; they were 9- by 9-inch false-color infrared red composites and 18- by 18-inch black-and-white prints of band 5 only (scale 1:500,000).

Geohydrologic Setting

Mali, Niger, and Upper Volta occupy part of a large relatively stable structural platform that extends across most of northern Africa. The platform is formed principally by Precambrian basement rocks which are discontinuosly mantled by thin sedimentary rocks of Paleozoic to Cenozoic age. Imposed upon this broad platform are several gently downwarped sedimentary basins which are bordered by low uplands and plateaus (Archambault, 1960). The basins are major features, about 600 km or more across. Mali lies in parts of two of these basins, the Bassin du Soudan and the Bassin du Niger (fig. 1). Niger lies mainly in the Bassin du Niger, and Upper Volta lies in low uplands along the southern flanks of both basins. The Precambrian basement rocks, including a variety of granitic and foliated metamorphic rocks, are exposed mainly in the uplands and plateaus (Marvier, 1952). The Paleozoic and Mesozoic sedimentary rocks crop out along the flanks of the structural basins or lie at relatively shallow depth beneath Cenozoic sedimentary rocks which occupy the central parts of the basins (Archambault, 1960). Mesozoic strata, however, are not recognized southwest of a line trending roughly northwestward through Niamey and Tombouctou. Surficial deposits, principally of Quaternary age, are thin but widespread—occurring mainly as stabilized and active dune-sand deposits, as stream alluvium, including deposits of the Inland Delta of the Niger River, as scattered terrace deposits, and as widespread laterite duricrusts. The laterite forms surficial ferruginous crusts 1 to 10 m thick over more than 80 percent of Upper Volta, southern Mali, and southern Niger and lends a harsh reddish-brown aspect to the landscape. All the consolidated rocks and unconsolidated deposits yield water to some extent, but the principal ground-water reservoirs are in the coarse facies of the Mesozoic and Tertiary sedimentary rocks occupying the central parts of the downwarped basins and in the unconsolidated alluvium, especially the deposits along the Niger River. Additional descriptions of thickness and lithology and the associations of the rocks with vegetation, with ground-water supplies, and with farm and range parameters are summarized in table 1.

The LGA countries lie principally in the low (200–650 m above mean sea level) semiarid Sudan and Sahel Savanna and the arid Saharan regions of West Africa where rainfall occurs only during the high-sun months of May to October. The southern parts of these countries receive more than 1,000 millimeters of rainfall annually (fig. 2). Rainfall during the high-sun period has to sustain plant and animal needs throughout the long dry season that lasts roughly from October to May. Bamako and Ouagadougou commonly have a dry season of 5 to 7 months and receive less than 25 mm of rain during this time. At Niamey, Gao, and Mopti, the dry season lasts from 7 to 9 months; at Tombouctou, the dry season is longer than 9 months (Church, 1968). Thus, any prolongation of the dry season or shortening of the rainy season

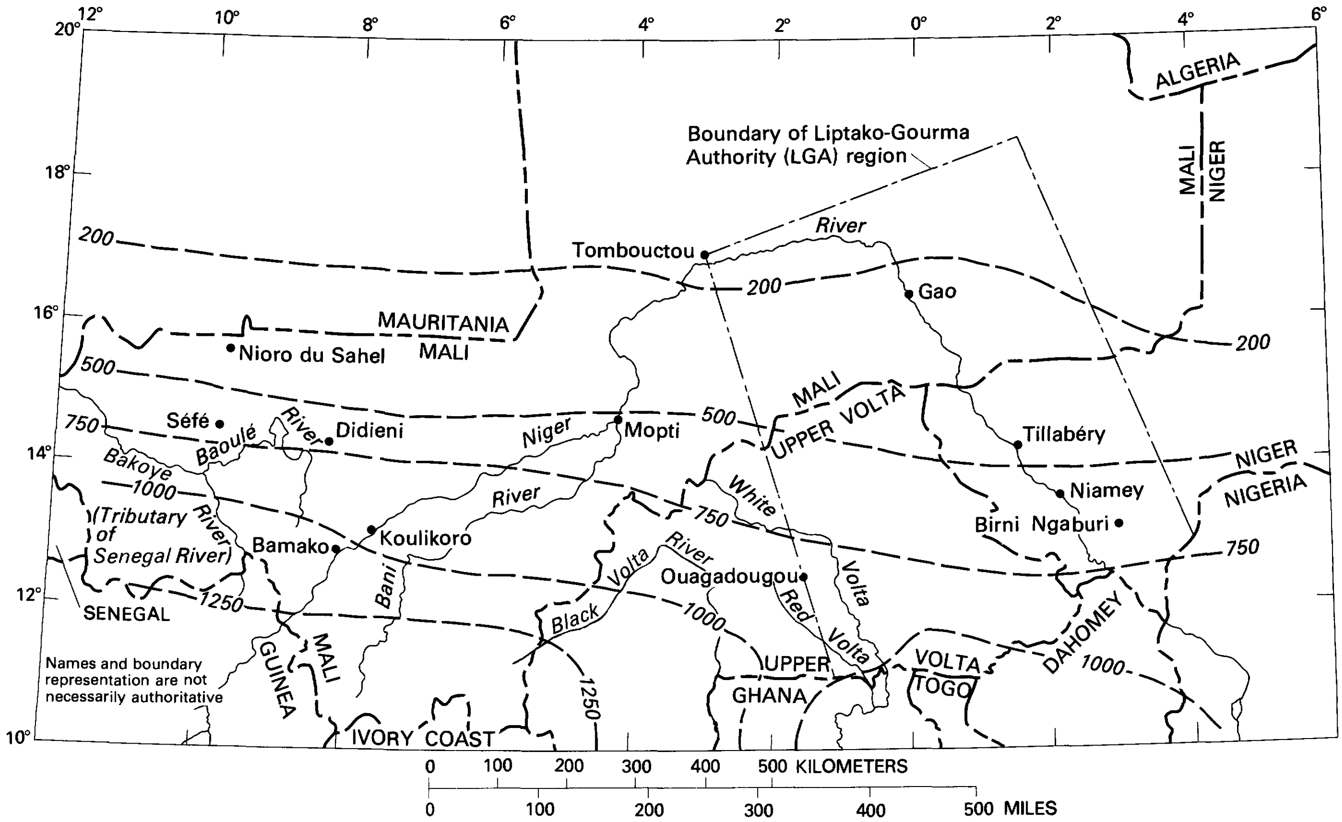


FIGURE 2.—Mean annual precipitation, in millimeters, in parts of Mali, Niger, and Upper Volta (taken from Archambault, 1960, fig. 2).

has disastrous effects on the farming and grazing economy of the region. The precipitation decreases northward, and, in northern Niger and in Mali north of Gao, precipitation is less than 200 mm annually. There, rains fall mainly during July and August. Because of prevailing high mean annual temperatures (27 °–29 °C), evapotranspiration is also high. Therefore, during the dry season, most streams and small reservoirs dry up, soil moisture and shallow ground-water supplies are depleted, and the range vegetation becomes dormant.

The Niger, the Red, White, and Black Voltas, and the Senegal Rivers draining the Sahelian region of West Africa receive most of their runoff from precipitation that falls on a rather low but broad highland that extends east-west across northern Guinea, southern Upper Volta, northern Dahomey, and southern Mali. Annual rainfall in this highland commonly ranges from 1,000 to more than 1,250 mm (fig. 2). The Niger and Volta Rivers all empty into the Gulf of Guinea. The Volta Rivers enter the Gulf through Lake Volta in Ghana, but the Niger takes a long circuitous route northward to the edge of the Sahara near Tombouctou, where it bends eastward and then southeastward past Gao and Niamey (fig. 1) on its course to the Gulf of Guinea. The Senegal River flows generally northwestward to the Atlantic Ocean north of Dakar. These three great rivers and their main tributaries are in flood stage during the rainy season; this flooding is commonly referred to as the annual flood. In central Mali, the annual flood of the Niger River spreads spectacularly over much of a vast Inland Delta where flood-retreat farming is practiced extensively (fig. 1).

Savanna Vegetation

The semiarid savanna vegetation of West Africa, from its southern limit at the Tropical Forest Zone, grades progressively through open woodland to shrubland to its northern limit at the Sahara. The major vegetation communities are oriented as a series of east-west parallel bands in response to the dominant rainfall gradient across Africa. The gradient of decreasing precipitation toward the north is accompanied by a progressive change in the character of the vegetation. To the south, where rainfall is highest, the vegetation comprises tall trees with large evergreen leaves; there is virtually no grass understory. This is the true forest. Proceeding northward through 10 or 15 degrees of latitude, these large-leaved forms are gradually replaced by short trees and shrubs which have small often finely divided drought-deciduous

TABLE 1.—*Brief description of the stratigraphic units and their utilization by man in the areas near Bamako, Mali, Niamey, Niger, and Ouagadougou, Upper Volta*

Era	Period	Epoch	Stratigraphic unit	Distribution and thickness
Cenozoic	Quaternary	Holocene	Dune deposits near Niamey (dunes were not inspected in other areas)	Small discontinuous areas on terraces and slopes near the Niger River and on broad gentle slopes underlain principally by laterite away from the river; generally less than 10 m thick.
Cenozoic	Quaternary	Holocene	Alluvial deposits: Channel alluvium of Niger River (excluding deposits of the Inland Delta)	In wide and braided channels of the Niger River and in adjacent low terraces inundated by the annual flood.
Cenozoic	Quaternary	Holocene	Alluvial deposits: Flood-plain alluvium along Niger River (excluding deposits of the Inland Delta)	Forms terraces generally not inundated by the annual flood; terrace is 3 to 6 m high (above low flow stage of the river) and from a few meters to more than 2 km wide; unit generally thin, in places less than 6 m thick, particularly near Bamako where older consolidated rocks are exposed in the river.
Cenozoic	Quaternary	Holocene	Alluvial deposits: Gray alluvium	Underlies central areas and much of gentle slopes of broad flats and narrow flood plains along streams in small valleys in uplands away from the Niger River; unit is thin and is less than 1 m thick in much of the broad flats; locally unit is more than 3 m thick along streams.
Cenozoic	Quaternary	Pleistocene(?)	Alluvial deposits: Yellowish-buff alluvium and equivalents	Exposed on gentle slopes forming broad flats; at many localities, it comprises bulk of alluvium of the broad flats; unit forms conspicuous terrace 5 to 15 m high along the Niger, Senegal, and White Volta Rivers and a lower terrace along some of their tributaries; thickness varies locally, but in places the unit probably is greater than 20 m thick.
Cenozoic	Quaternary	Pleistocene	Alluvial deposits: Brown alluvium in vicinity of Ouagadougou	Exposed mainly in the perimeter area of broad flats; thickness is unknown.
Cenozoic	Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)	Laterite	Exposed over about 80 percent of the area on ridges and mesas, on steep slopes, on colluvium or consolidated rocks, over broad plains, and on river terraces; also present beneath alluvial deposits; 1.5 to 10 m thick.
Cenozoic	Tertiary	Miocene	Continental Terminal (Archambault, 1960)	Present only near Niamey (in Bassin du Niger) where it underlies laterite capped buttes, ridges, and broad slopes; 100 to 200 m thick.
Cenozoic and Mesozoic	Tertiary and Cretaceous	Eocene	Cretaceous-Eocene sedimentary rocks undifferentiated	Not exposed, present only in subsurface of Bassin du Niger near Niamey; more than 400 m thick.
Paleozoic	Ordovician		Grès Ordovicien (Archambault, 1960)	Forms uplands in Bamako area; not present or not recognized in the other areas; unit generally capped by laterite; 50 to 200 m thick.
	Precambrian		Basement complex	Few small isolated outcrops in area.

TABLE 1.—*Brief description of the stratigraphic units and their utilization by man in the areas near Bamako, Mali, Niamey, Niger, and Ouagadougou, Upper Volta*—Continued

General lithologic description	Utilization by man: Ground-water supplies	Utilization by man: Farm and range
Consists of active and stabilized sand dunes; includes many composite dunes and a few climbing and falling dunes; older dunes show a slight amount of consolidation and development of soil.	Generally too thin and of too small an areal extent to be a source of ground water; highly permeable sand allows much infiltration and little runoff from precipitation.	Extensive local use for crops; main unit farmed between Niamey and Dallol Bosso; when soil and vegetation cover of stabilized dunes are disturbed by cropping, overgrazing, or by natural causes, the dunes are liable to severe wind erosion and blowout activity.
Consists chiefly of unconsolidated sandy and silty alluvium, many large sand bars show huge current marks.	Deposits are permeable and yield water to shallow temporary dug wells during low flow periods, but annual flooding prohibits development of the unit by permanent wells.	Partially utilized in flood-retreat farming and for grazing; unit can be farmed much more intensively.
Consists of unconsolidated sand and silt containing a minor amount of gravel	Yields dependable supplies of ground water to wells because of its proximity to the river; well yields probably are not large because of the general thinness of the unit, larger quantities of water, perhaps sufficient for some irrigation, can be obtained by construction of collector wells in the unit.	Partially used for farming and for orchards; grass and brush foliage supports considerable stock; unit comprises best arable land in the Bamako and Niamey areas and can be more intensively developed for farming, with water diverted from the Niger River.
Consists of unconsolidated to very slightly consolidated light-gray to grayish-buff clay and silt; contains some sand, little gravel—mainly of grit and small pebbles; contains considerable organic material especially along streams.	One of the alluvial deposits supplying small amounts of water to dug wells of villages and fields along small streams; unit probably lies above the water table in most of the broad flats [Figure 9 shows two typical conditions of occurrence of some of the dug wells that have become dry during the past few years.]	Unit is widely cultivated everywhere, but it comprises the only arable land in the uplands near Bamako and Ouagadougou; in many places, the unit is 30 cm thick, thereby limiting its usefulness for farming, especially to deep plowing even if farm machinery would become available; many villages are situated on the unit because they are clustered in areas where there are shallow water supplies and arable land.
Consists of slightly consolidated yellowish-gray, light-brown, or buff clay to silt containing considerable sand and little pebble-sized gravel; unit generally is yellowish in the Bamako and Ouagadougou areas and brownish near Niamey; as much as uppermost 2 m of unit may show weak development of laterite.	Probably supplies a small amount of ground water to many shallow dug wells constructed in the broad flat areas.	Development of laterite in the topmost beds of the unit precludes its use for farming of crops, although the unit supports range grass and browse vegetation; unit probably can support orchards and shade trees; unit is severely sheet eroded especially near villages where land has been subjected to extreme overuse by man's activities.
Consists of weakly to moderately consolidated brownish-gray silt to mainly pebble-sized gravel composed of laterite detritus, gravel concentrated mainly near the laterite outcrops; silty and sandy parts are in the downslope areas; at many places, unit is overlain by moderately hard laterite forming a layer more than 1.5 m thick.	Yields small amounts of water to dug wells.	Used as rangeland even though many exposures are nearly denuded of vegetation and are subjected to severe sheet erosion; laterite detritus in unit and associated laterite is excellent for road metal.
Consists of several units, each unit has different thicknesses, composition, amount of cementation, bedding features, and included alluvial detritus; generally hard to very hard; more ferruginous near Niamey and Gao than in other areas; older units may be siliceous and contain fractures formed along joints.	Part of laterite underlying alluvial deposits apparently yields small amounts of water to dug wells; fractures aid infiltration from precipitation through the laterite and into the underlying rocks.	Because of extensive distribution, unit forms principal rangeland of the area; excellent as building stone and makes attractive walls; when crushed, used as road metal.
In a few exposures that were inspected, unit consists of silty to sandy deposits modified or partly altered during formation of the overlying laterite.	Where saturated, unit should yield dependable small to moderate supplies of water to drilled wells.	Generally exposed only in steep slopes that are undergoing severe erosion; forms a minor part of the rangeland.
Includes, in descending order, the Eocene, Middle and Upper Cretaceous, and Continental Intercalaire (Archambault, 1960); consists of clay to gravel deposits; upper part mainly clay and sand, lower part mainly sand and gravel.	Where saturated, unit should yield dependable small to moderate supplies of water to drilled wells.	————
Consists mainly of firmly cemented sandstone that can be divided into several distinct units; units are fractured extensively along joints and small faults.	Where saturated, probably would yield small amounts of water to drilled wells; where unit is highly fractured, well yields would be greatly increased.	Mainly used for grazing; insufficient amount of soil developed on unit restricts farming.
Consists of granitic and metamorphic rocks; some of metamorphic rocks are standing on end; rocks are deeply weathered to more than 15 m in the few exposures inspected.	Weathered part of unit is known to yield small amounts of water to dug wells near Ouagadougou; where rocks are highly fractured, they probably would yield some ground water to drilled wells.	Small exposures form minor part of rangeland.

leaves. The changes in leaf morphology and plant stature are accompanied by an increased openness of the woody components, the openings between the woody plants occupied by grasses. The number of thorny species also increases. Terms widely used in West and Central Africa for the dominant transcontinental vegetation zones from south to north are Guinea Savanna, the Sudan Savanna, and the Sahel Savanna (fig. 3).

A vegetation gradient comparable to the south-to-north cline of vegetation types can be seen locally within the Guinea and Sudan Zones in changes that proceed from moist river terraces to the relatively dry uplands. River terraces within these regions contain more moisture for the plants than local precipitation alone provides, and the rivers are bordered in many places by narrow strips of tall large-leaved trees whose main areas of distribution lie hundreds of kilometers to the south. The term "fringing forest" has been applied to these narrow strips of dense vegetation. This type of forest is comparable to the "gallery forest" of North America.

The present savanna vegetation in West Africa has been exposed to more or less continuous heavy use by man for centuries and perhaps millenia (Hopkins, 1965) and consequently has been altered greatly (fig. 4). Since the late 1960's and early 1970's, all zones of the savanna have been under severe stress from intensified drought conditions, coupled with increased population pressures of man and proliferating domestic herds built up during the 1950's and early 1960's, largely with inadequate regard to proper management practices. (A wet cycle prevailed in the region from about 1955 to 1966.) Where lands are cultivated, a combination of cutting, burning, and fallowing is also practiced. This swidden (slash-and-burn) form of agriculture has changed the area of earlier existing dense forest vegetation to its present form of open forest or shrubland. These practices have increased the availability of farmland and rangeland for man's use but have greatly modified or obliterated the original vegetation of the Sudan and Guinea Zones. Contrary to much of popular opinion, the Sahel vegetation (north of the 450-to 640-mm isohyets) has been less affected by man's activities than that of the two southern zones where rainfall is greater (Church, 1968). In the Sahel, there is less grass to carry fires, population levels are low, and possibilities for cultivation without irrigation are slight, especially in areas adjacent to the Sahara; consequently, the natural vegetation has been modified only by grazing. Accordingly, the savanna areas of most critical concern for maintaining a proper balance between the

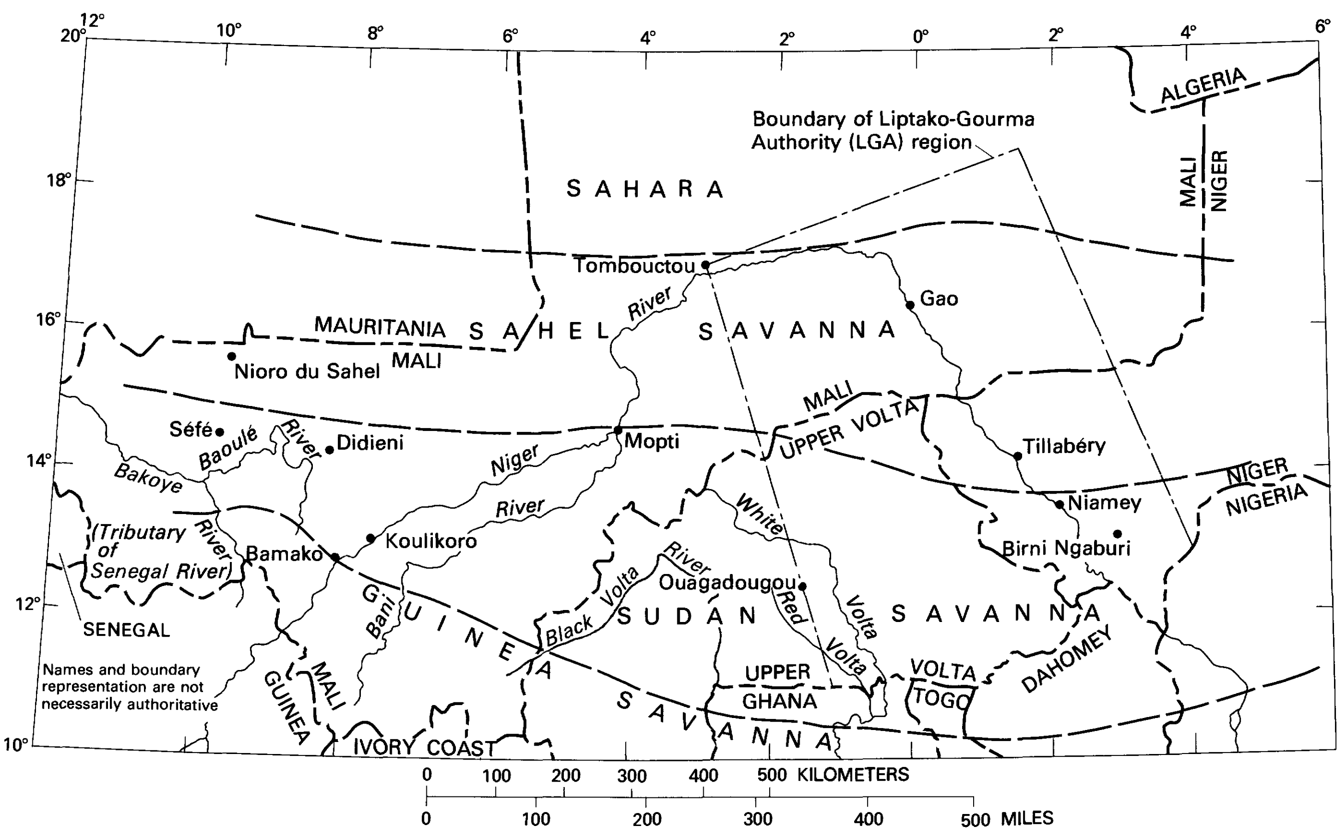


FIGURE 3.—Vegetation zones in parts of Mali, Niger, and Upper Volta (taken from Keay, 1959).

FIGURE 4.—Photographs taken along the White Volta River showing influence of man's activities on vegetation and terrain.

A. Vegetation and terrain show little effect of man's activities during the year ending May 1974. Grass has been moderately grazed, and some branches have been cut from the tree in center middle ground.

B. Grass understory vegetation has been somewhat altered by burning. The general absence of soil-holding vegetation allows for minor sheet erosion.

FIGURE 4.—Photographs taken along the White Volta River showing influence of man's activities on vegetation and terrain—Continued.

C. Burning has removed the grass and woody understory vegetation. A few trees have been cut for firewood; trunks and branches larger than about 10 centimeters in diameter are not utilized. The bark on some of the living trees is charred but is thick enough so that the trees are not injured by fires. This area, stripped of its ground cover, is susceptible to accelerated sheet erosion.

D. Wood cutting and burning have removed all the vegetation on a low terrace formed from easily erodable yellowish-buff alluvium. A small village lies just to the left of the picture. The White Volta River lies just off the photograph to the right. Denudation permits development of accelerated sheet erosion which soon will be accompanied by severe gullying.

natural vegetation and man's use of the land are to the south, where woodland is constantly being replaced by grassland, rather than to the north, where the original vegetation has been less detrimentally affected by man.

The Sudan Savanna, which lies in a belt 200 to 400 km wide north of the Guinea Savanna, includes trees 8 to 16 m high, many of which belong to the same species found in the zone to the south. Especially common are the doum palm (*Hyphaene thebaica*), danya (*Sclerocarya birrea*), and soapberry tree (*Balanites aegyptiaca*), all of which increase in dominance northward toward areas of increasing aridity and are represented little or not at all in the Guinea Savanna. Grasses grow 1 to 1.75 m high. Because the grass species in the Sudan Savanna are less course than those to the south, they are more valued as forage and less often deliberately burned (Church, 1968).

In the region of Bamako, which lies on the border between the Guinea and Sudan Zones, and Ouagadougou, which is in the central part of the Sudan Savanna (fig. 3), the following geobotanical categories are recognized: (1) alluvial flats and valleys (generally containing ground water with a shallow water table), (2) uplands, (3) slopes of buttes and ridges underlain by laterite and (or) sandstone, and (4) the riverine fringing forest. In each of these categories, the vegetation has been greatly altered by man's activities. For example, villages in the vicinity of Bamako occur at regular intervals of about 5 to 15 km. The land is heavily cultivated around the villages, and areas between villages usually are cultivated as well. All the uncultivated vegetation is in some stage of recovery from burning or clearing. Presence of grasses is variable in the Bamako area, as elsewhere in the savanna zones, largely because of local differences in environment that affect moisture availability for plant growth, differences in the intensity of grazing, and in the frequency and timing of bush fires.

On the alluvial flats, provided that destruction of the vegetation is not extreme, the first category of vegetation comprises such trees as the shea butter tree (*Butyrospermum parkii*), locust bean tree (*Parkia biglobosa*), dry-zone mahogany (*Khaya senegalensis*), African rosewood tree (*Pterocarpus erinaceus*), and species of *Combretum*. Some of these trees, such as the shea butter, are of economic importance and are preserved even in areas of heavy disturbance. Another economically important tree that is closely associated with villages and can be seen standing sentinellike in fields is the baobab (*Adansonia digitate*). Many of the same species that grow on the flats grow on the laterite-capped ridges and buttes (vegetation category 2), where edaphic conditions are drier than on the alluvial flats, but the plants are reduced in size. In addition, the kapok tree (*Bombax costatum*), harike (*Anogeissus leiocarpus*), and figs (*Ficus* species) are present. Along the slopes of scarps, particularly of the buttes and hillslopes, where edaphic conditions are intermediate between the ridge and butte surfaces and the alluvial flats, the vegetation (category 3) is usually denser than that above or below and probably attains 75- to 100-percent foliar coverage during the rainy season. Here may be the most northerly habitats for the tse-tse fly. These hill-slope forests, where especially dense, stand out sharply on properly enhanced Landsat imagery (fig. S–1A). The fourth category of vegetation in the Bamako and Ouagadougou regions is the riverine fringing forest. A partial listing of the trees in this forest includes a palm (*Raphia sudanica*), a fig (*Ficus capensis*), a cola (*Cola cordifolia*), and malmo (*Syzygium guineense*).

The driest area the writers were able to examine in detail was in the region of Niamey, Niger, which is near the northern limit of the Sudan Savanna (fig. 5). One of the striking differences between the vegetation in this region and that toward the southern limit of the Sudan Savanna near Bamako is the increase in small-leaved species such as the Acacias and in the spiney plants. One of the most common spiney trees is African myrrh (*Commiphora africana*). Shrub communities grow on dry sites, dominated by a species of *Combretum*. The shrub canopy grows to about 2 m in height and is interrupted irregularly by a low tree, the soapberry. In general, the grasses are shorter and much less abundant in the vicinity of Niamey than in the region of Bamako and Ouagadougou. Fringing forests of evergreen broad-leaved trees are absent from this region (and northward), the watercourses being lined by certain drought-deciduous Acacias. As a consequence, intermittent stream courses do not stand out sharply on Landsat imagery taken during the dry season.

Landsat Imagery in Relation to Range and Water Assessments

In the following sections the writers describe the main applications they discerned for use of Landsat imagery in resolving land-resources problems affecting the people of the LGA countries. In addition, tentative answers to some pertinent questions relative to the use of Landsat imagery in range and water management are given in table 2.

FIGURE 5.—Photograph showing west side of the Niger River valley near Niamey, Niger. In the foreground, a species of *Combretum* (dominant) and *Pterocarpus* (left) on detritus formed from a terrace capped by laterite. This photograph, taken on May 18, 1974, near the end of the dry season, shows many leafless plants, a typical condition for this time of year. Doum palm, soapberry tree, shea butter tree, among other trees, grow on the light-colored sandy terrace deposits and dunes in the background. This area is in the northern (dry) part of the Sudan Savanna zone. Two buttes along the horizon consists of fine-grained "Continental Terminal" semiconsolidated sand and clay capped by resistant laterite duricrust.

Three main factors are important in the use of the imagery and to its interpretation:

1. Adequate onsite investigation is essential for accurate identification, mapping, or monitoring of geohydrologic, vegetative, and agricultural phenomena.
2. Many conclusions concerning hydrologic features, disease, and insect control must be deduced indirectly from the imagery by observing geologic and vegetational features. For example, shallow ground-water zones and tse-tse fly habitats are not identified by making direct observations of water and flies; the presence of these is inferred by correlation of conditions observed in the imagery with geological and vegetational features known to be associated with water and flies. Similarly, the extent of arable soils can be determined principally by relating the occurrence of such soils with geologic features that are readily discernible on the images.
3. The effects of man's use of the land must also be considered when interpreting Landsat imagery. In areas visited by the writers, the land around most villages is denuded of grass and forbs as a result of trampling by men and livestock, overgrazing, brush burning, and cultivation (fig. 6). These activities produce accelerated sheet erosion and wind deflation, both of which exert a profound effect on the

distribution and thickness of arable soils. Lastly, so much of the rangeland has been burned each year or heavily grazed or cleared during the past centuries that no vegetation is left that can be considered as unmodified.

River-blindness control

River blindness (*Onchocerciasis*) is a disease of man caused by a filarial worm (*Onchocera volvulus*). The causative organism is transmitted by a black fly (*Simulium damnosum*). Outbreaks of this disease, which ultimately causes blindness, are common along rivers because the riparian habitat is essential for fly reproduction. *Simulium* eggs are laid in streams or ponds where they hatch. The larvae feed by straining microorganisms out of the water; however, slowly moving water carries too little food to the sedentary larvae, and they starve. Therefore, larvae survive most successfully at sites of fast-flowing water such as rapids or dam spillways (fig. 7).

Recently, a multinational effort was initiated to control river blindness (Tomiche, 1974). The approach taken is to kill the larvae at all the breeding sites in an area of 700,000 square kilometers in the Volta River basin. The larvae are killed by dropping from the air a specially formulated pesticide into streams at all known breeding sites. Accurate maps are necessary when preparing detailed flight plans for reaching known fly-breeding sites, and the absence of appropriate maps is hampering the programs along the Black Volta River (Frank Walsh, oral commun., 1974). Although Landsat imagery, because of its lack of sufficient resolution, does not appear useful in locating specific sites of fast water or rapids, it does have potential application for correctly locating a river system in regions for which maps are poor or incomplete and for identifying small reservoirs that may be breeding sites.

The location of dams has become a critical step in the control program because dam spillways often harbor large populations of the fly larva (Tomiche, 1974). The stockwater dams are difficult to keep track of because they may last only a few years and because new dams are constantly being built (fig. S-2B). Landsat band 7 imagery or color-composite imagery can be especially suited to locating these bodies of water if the reservoirs are larger than about 200 m in diameter (30 hectares in area). For elongate reservoirs, the total area may even be smaller.

FIGURE 6.—Photographs showing effects of man's activities around small villages.

A. Newly hand-cultivated field adjacent to a recently dug well (indicated by circular concrete ring) near Ouagadougou, Upper Volta, May 14, 1974. The well obtains ground water from weathered granite, which in this area underlies a surficial mantle of alluvium and laterite.

B. Accelerated erosion along pathway leading through newly planted fields near Ouagadougou, Upper Volta. Erosion was caused by early rains of the 1974 wet season.

TABLE 2—*Tentative assessment for relating Landsat imagery to selected problems in range and water management in the Liptako-Gourma countries*

(1) Can shallow water tables and zones of ground-water discharge be identified and their areal extent mapped?

Shallow water tables are difficult to separate from zones of ground-water discharge on Landsat images because both occur at or near the land surface and both are associated with dense growths of vegetation. Discharge of ground water, however, maintains flow of streams and ponds in stream channels well after the end of the rainy season. Dense growths of vegetation are shown on the imagery along some streams, principally in alluvial valleys, near Bamako and Ouagadougou (figs. S–1, S–2; frames 1117–10232 and 1095–10000 taken in October and November 1972, respectively). The heavy growth suggests the presence of a shallow water table and probably ground-water discharge into the stream channels at the time the imagery was taken. For best results in differentiating between the two conditions, imagery taken periodically throughout the dry season should be examined for changes in vegetated areas affected by shallow ground-water discharge zones.

(2) Can weathered or fracture zones in the Precambrian crystalline basement rocks, likely to be productive of ground water, be identified?

Generally, the Precambrian basement rocks are concealed by laterite duricrust or by a thin surficial mantle of alluvium. Near Ouagadougou, hand-dug wells, penetrating through the laterite, yield small amounts of water (enough for stock, villages, and bucket irrigation of small cultivated plots) from deeply weathered regolith developed in the upper part of basement rocks. This area of low relief is identifiable on the imagery because of the generally light, rather even color tone and general lack of conspicuous drainage features (fig. S–2).

Linears identifiable in the imagery in areas of consolidated rocks may be related to faults, fractures, and joints along which water movement and accumulation are facilitated. Weathering in such zones, and especially at points of intersection, would improve the potential for accumulation of important sources of water.

(3) Can good sites for surface-water catchments be identified?

Sites favorable for small surface-water catchments are widely distributed because of the general low permeability of the older consolidated rocks as well as the younger surficial deposits. Ephemeral lakes and ponds, which are discernible with repetitive imagery coverage, give clues as to locations for potential catchment sites that can be improved by artificial excavation and (or) low earth dams. Constrictions or narrows in stream channels in areas of outcropping consolidated rocks can also be identified to give clues for the location of small dams for surface-water catchments. Larger areas that generally are unfavorable for surface-water catchment sites are mainly those mantled by thick, relatively permeable, dune-sand deposits or those in areas of intensively fractured rock where the water table is at considerable depth. The main dune-sand and principal fractured areas are identified readily on the images (figs. S–4, S–6*B*). The smaller areas, where surface-water catchments may not be successful, are on sandy terraces and slopes of the Niger River valley, on the sandy alluvium of at least part of the dallols, and on sandy alluvium along small streams that drain principally dune-mantled areas. The Landsat imagery aids in recognizing these areas, which generally appear light-colored in comparison to adjacent laterite duricrust, consolidated rocks, or the Continental Terminal where capped by laterite duricrust.

(4) Can land potentially useful for irrigated crop production be identified?

The Niger River valley is, of course, the most obvious choice. Much of the arable land is identifiable on the Landsat imagery and, with onsite inspection, can be mapped in considerable detail using Landsat imagery at a scale of 1:250,000. (See section on "Factors affecting availability of arable land.") Only the flood plain of the Niger River and the Inland Delta, however, are capable of supporting large-scale farming operations. In these areas, large amounts of water are available for irrigation by diversion from the Niger River and, in the Inland Delta, from the Niger and the Bani Rivers. Supplemental ground water can also be obtained for irrigation in these areas from properly constructed wells.

Small vegetable plots can be farmed along the various segments of the braided channel of the Niger River, as for example near Niamey (fig. 12). The braided channel is easily mapped by the imagery (figs. S–4, S–5). Analysis of Landsat imagery is useful for inspection, leading to final selection of the channel reaches most suitable for farming throughout the Niger River valley.

Flood-retreat cultivation is the principal farming technique practiced by the people living along the Niger River in Mali. It is practiced to a lesser extent in Niger, where this method of cultivation is not well developed (Church, 1973). The lands near the river are seasonally flooded, and, as the floodwaters recede, the farmers use the wetted lands to cultivate a definite sequence of crops: maize, grain sorghum, sweet potatoes, cucurbits, tomatoes, and beans in order from top to bottom on the slopes. Grain sorghum is sown on the gently sloping outer valley floors and rice is sown on the flattest areas of maximum depth of inundation. Landsat imagery and the capability Landsat provides for repetitive observation make it well suited for determining the maximum limit of flooding, thereby providing a means of predicting crop size in advance of harvest. By knowing a crop yield potential in advance, impending needs and requests for assistance can be tailored accordingly.

(5) Can distinctions in the relative seasonal productivity of grass and browse vegetation be made from the imagery?

The Landsat imagery is ideally suited for detection of seasonal trends in rangeland plant growth. Qualitative differences can be observed on sequential imagery provided observations are made on enhanced images; for example, color composite photographs or diazochrome overlays. To obtain quantitative data showing seasonal trends, sophisticated ratioing techniques can be used to eliminate the undesirable effects of variables such as haze and sun angle. These techniques require the use of computer-compatible tapes or, if images are used, a video system with a capacity for ratioing and electronic slicing.

The ability to detect the density of crops in fields as a measure of crop success and crop yield would be extremely useful (W. Morris, oral commun., 1974), although the main crops, such as millet and sorghum produce a sparse cover that might be difficult to detect. The time for analysis and degree of sophistication required to assess the applicability of the data for crop-yield estimate was beyond the scope of this project. Work by others, however, indicates that the data can be used to aid in identifying crop types and estimating yields for fields with areas of 32.4 hectares or greater (Wigton and Von Steen, 1973; Morain and Williams, 1973).

TABLE 2—*Tentative assessment for relating Landsat imagery to selected problems in range and water management in the Liptako-Gourma countries*—Continued

(6) Can areas of relative overgrazing and undergrazing be identified from the imagery?

Overconcentration of livestock around existing water points has led to complete denudation of vegetation in many localities. Landsat images clearly show some trails leading to water points as elongate light-colored streaks (fig. S–3). These were not examined in the field, but it is apparent that the trails appear light colored on the images because of denudation through overgrazing. In support of this, villages are often clearly discernible as light areas (fig. S–3). The high reflectance at the village sites does result from denudation by overgrazing, wind deflation, and sheet erosion, as well as perhaps other causes.

(7) What is the relationship between the laterite duricrust of interfluvial upland surfaces versus grass and browse density? In the absence of perennial water, soils derived from what types of geologic terrains are most conducive to productive grazing and browse lands?

Alluvial soils (mainly those derived from the gray alluvium) are the most productive grazing and browse lands. (See section on "Factors affecting availability of arable land.") Grass and shrub foliage is far denser there than on the adjoining laterite terrain. At many places, the laterite duricrusts form bare wind-swept surfaces nearly devoid of soil and vegetation. The Landsat imagery has been demonstrated to be highly useful in the distinction between alluvium and laterite in the Ouagadougou area (fig. S–2*B*) and near Niamey and Tombouctou (figs. S–5, S–6). More subtle distinctions between the three types of alluvia (brown, yellowish-buff, and gray) will require special Landsat false-color composites.

(8). What do Landsat data tell us about desert encroachment as indicated by migrating sand dunes and wind and sheet erosion, accelerated in either the current drought cycle or by antecedent drought conditions?

Migrating or active sand dunes do not extend as far south from the Saharan region as do stabilized dunes (fig. S–6B). Stabilized west-southwest—east-northeast longitudinal dunes near Tombouctou are covered by weakly developed slightly reddish-brown soils. These dunes are not now impeding the flow of the Niger River, although they have doubtless influenced the river's course and flow regime in the past. At present, the river flows through these dunes in one wide main channel as well as in a system of tributary channels, many of which carry water only during the flood seasons.

Both the active and stabilized dunes are easily mapped by the Landsat imagery. Denudation of vegetation and concommitant blowout activity can also be recognized on the images. To define and to separate the natural from the man-induced effects—and to determine whether these phenomena are a result of the current drought or the aggregate effects of man's abuse of the land during previous decades or even centuries—would, of course, require much onsite investigation.

Accelerated sheet erosion, including severe gully erosion, is commonly observed in all the areas the writers were able to visit or to discern on the images. (See section on "Accelerated Erosion.") The present advanced stage of gully dissection and the large area involved in accelerated erosion strongly suggest that these processes have been in progress for several decades. In the localities visited by the writers, man's activities in recent decades appear to have aggravated these processes more than have adverse effects of the present drought cycle.

Continuous monitoring by Landsat can provide additional information that may be useful in the River-Blindness Control Program. Seasonal changes noted in the flow regime of rivers might indicated conditions favorable for growth of the black fly larvae. According to Malian officials, considerable relocation of the village peoples takes place in West Africa, principally because of (1) disease (including river blindness), (2) water problems (from drought and pollution), (3) changing cultivation practices, and (4) superstitions. Large villages are readily discernible on the images, and areas having or lacking small villages are visible (fig. S-3). Thus, repetitive Landsat observations could be made to locate new villages and abandoned old ones.

Tse-tse fly control

The life cycle of the tse-tse fly, which is the main carrier of bovine encephalitis (*Nagana*), has a relationship to the density of vegetation. This relationship is being exploited in a program to eliminate this disease from large tracts of land in Mali. The tse-tse fly is inactive at midday, during which time it seeks shade within nearby forests. The fly can be controlled by spraying small clumps of these forests with insecticides or, where large areas of sheltering forest occur, by spraying the forest peripheries. The tse-tse fly moves over rather short distances, probably spending its entire life within an area as small as 1 km². The fly is viviparous, producing a single fully grown larva which crawls to a sheltered spot and then pupates directly without feeding. The pupal stage lasts for several weeks. Spraying with one insecticide application does not effect control because the killed adult flies are shortly replaced by a new generation that develops from the sheltered pupae. A second spraying soon after the new crop of offspring emerges is usually effective, however (K. J. R. Maclennan, oral commun., 1974).

In attempts to eradicate the fly permanently, a two-step scheme is being practiced. First, a patch of infested forest is isolated by clearing the land around the target area. The barrier of cleared land needs to be wider than the distance the fly normally migrates, or roughly 1 km. After construction of the barrier, the isolated forest patch is sprayed with pesticide in the manner noted above. Hopefully, the combination of these two steps will make areas of forest habitable that must now be avoided.

Landsat imagery can be used to locate the dense stands of trees, especially in areas where much of the vegetation has been thinned out by human activity. Here, the clumps of dense forest are clearly distinguishable from the surrounding vegetation if viewed at a season when the open mainly cultivated lands are inactive. Figure S-1*A* shows several areas of dense forest where insecticide spraying might be appropriate.

Bush-burning monitoring

The prime human force in altering vegetation in the Sahel appears to be bush burning, especially in the areas where annual rainfall exceeds 450 to 640 mm. The favorite period for burning is during the terminal stage of the dry season when, with vegetation at maximum dryness, combustion is more rapid and less controllable. Fires also burn hotter and cause greater damage to woody plants and perennial grasses during this period than they do at other times (fig. 8). The burning is widespread—from the arable alluvial flats to boulder-strewn slopes and laterite-capped ridges—and contributes to the overall harshness of the countryside. Proposals have been made to abolish or at least to limit bush burning to the early part of the dry season before the vegetation becomes overly dry. Such proposals, however, have not been accepted by the pastoral population because they use the fires primarily to stimulate early leafing of trees and other plants when the livestock are in most critical need of green forage after the long dry season. This is done in spite of the fact that the burning obviously eliminates or reduces the availability of dry grass and forbs and the food supply during the dry season's crucial terminal stage.

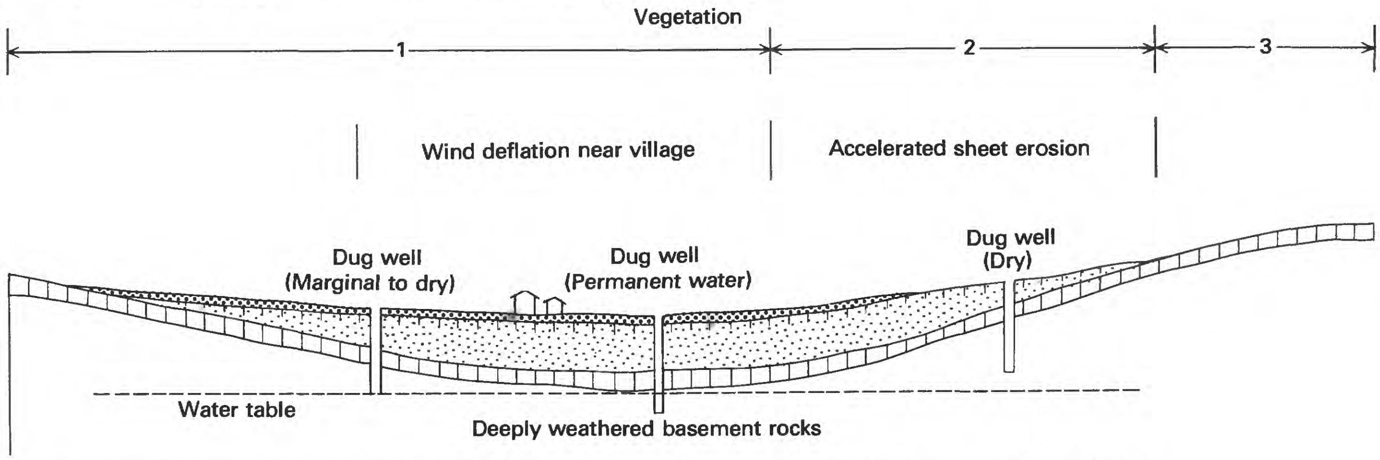
FIGURE 7.—Photograph of the White Volta River east of Ouagadougou, Upper Volta. Small rapids such as those in the middle ground and at the base of the stick dam are a possible habitat for black fly (*Simulium damnosum*) larvae, the insect vector responsible for spreading river-blindness disease (*Onchocerciasis*). Entire adult human populations over 30 years of age may become blind from this disease. Mud bricks are drying in the sun in the lower right of the picture. An earthen dam extending across the middle ground has been breached by the river.

Bush burning evidently has been practiced in Africa for 2,500 years or more (Hopkins, 1965; Church, 1968), and it was used widely during the dominance of the Rali, Songhai, and Ghana Empires as long ago as 1,000 years (Church, 1968). The reasons for burning the vegetation are varied: (1) man enjoys watching fire, especially at night, (2) man is negligent, allowing camp and cooking fires to burn unattended, (3) fires are thought to rid areas of parasites such as ticks and, through the clearing of the vegetation, of tse-tse flies, (4) clearing sections of the vegetation by burning makes cultivation and travel easier, (5) burning drives game animals from cover, and their capture is made easier, (6) burning stimulates early plant growth, (7) burning makes it easier for stock to graze on new sprouts, which otherwise would be obscured by the old growth, and (8) burning is thought to make it easier for the minerals contained in the plants to be returned to the soil. (See section on "Accelerated Erosion"; also, Hopkins, 1965, p. 56).

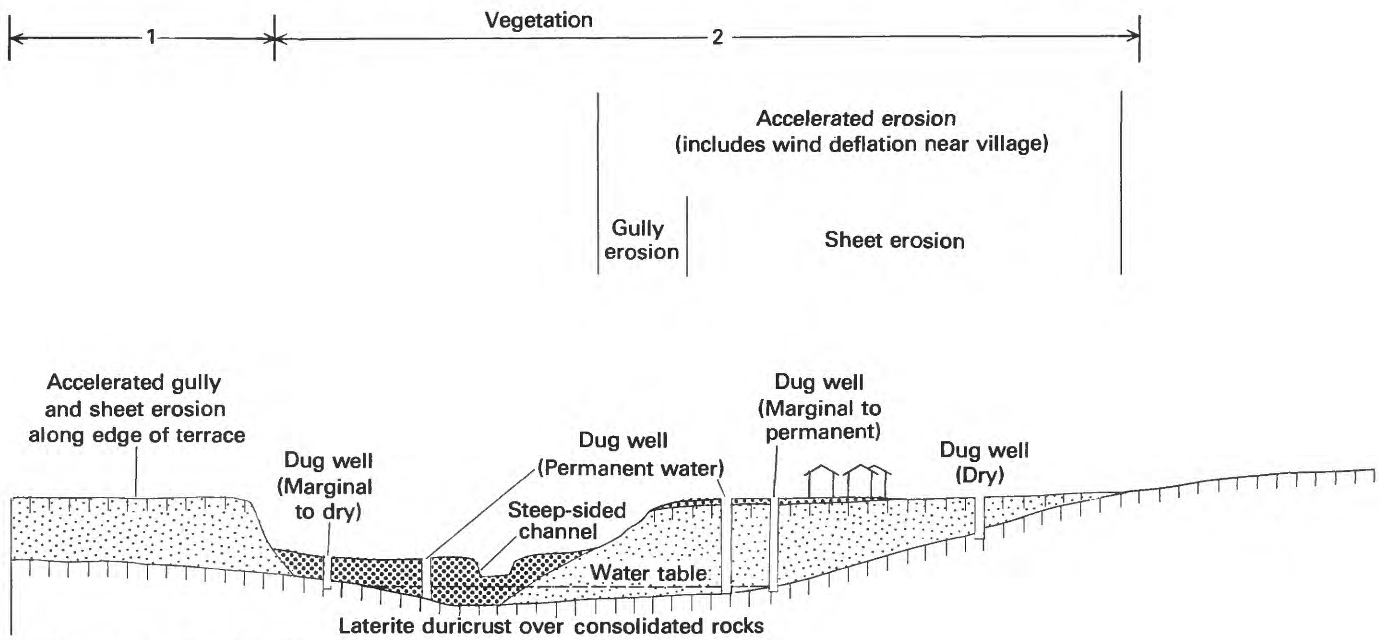
Landsat imagery has several applications to problems where knowledge of the location of recently burned areas is important. For example, in the event that attempts are made to limit bush burning or to control the season in which it occurs, Landsat imagery could be used during the establishment of such programs to detect fire frequency (figs. S-2*B*, S-3). Bush burning is forbidden by law in some areas, and Landsat imagery could be used to monitor the effectiveness of fire-suppression policies.

FIGURE 8.—Unattended unchecked brush fire northwest of Bamako, Mali, April 24, 1974. This small fire, burning through an area where grassy fuel is sparse, probably has a minimal effect on the ecosystem. In other areas where grass is dense, dry-season fires would burn intensely, eliminating much of the woody vegetation. Both lightly and severely burned areas probably would be visible on Landsat imagery.

FIGURE 9—Diagrammatic sections of small valleys near Ouagadougou, Upper Volta, and Niamey, Niger, showing distribution of laterite, alluvial deposits, areas of accelerated erosion, vegetation, and ground-water conditions.



A. Diagrammatic section of one of the alluvial flats or of a small valley not having terraces near Ouagadougou.



B. Diagrammatic section of a small terraced valley near Bamako.

EXPLANATION

Nonarable

Arable gray alluvium, represents extent of arable soil minus the areas mainly undergoing sheet erosion where the soil is too thin for cultivation

Yellowish-buff alluvium and equivalents, weakly developed laterite at top of unit

Laterite duricrust, generally 1 to 0.5 m thick

KEY TO VEGETATION

Figure 9*A*

(1) Vegetation a low open forest; variable composition depending on history of cultivation and burning; trees both evergreen and drought deciduous; grasses important element.

(2) Ground cover of grass all but eliminated where erosion is severe; trees and shrubs of original forest less affected.

(3) Vegetation a low sparse version of that on the alluvial area; grasses sparse or only locally abundant.

Figure 9*B*

(1) Many of the same trees as in areas with gray alluvium, but canopy here more open and height lower.

(2) Where cultivated, scattered baobab, shea butter, and mango trees remain; on fallow land, vegetation highly variable depending on burning and clearing history; trees, both large-leaved evergreen and small-leaved deciduous, dominate; grasses important.

Factors affecting availability of arable land

In the LGA countries, arable soils are developed chiefly on deposits of alluvial flats and in small valleys (including the ancient dallols, which are drainage systems developed during the Pleistocene Epoch), bordered mainly by uplands capped by laterite duricrusts, on flood-plain deposits along the Niger and Volta Rivers, on alluvium of the Inland Delta of the Niger River, and on eolian deposits of northern Mali and Niger (figs. S-4, S-6; table 1).

Alluvial flats and small valleys

The Ouagadougou area was selected to illustrate that mapping of alluvium and laterite is feasible through use of Landsat imagery (fig. S-2*B*). In an area of gentle planar topography at Ouagadougou, the alluvial deposits are thin and lie as discontinuous mantles over laterite which is exposed mainly on low ridges and stream channels (fig. 9*A*). To the west of the city is a moderately dissected region of flat-topped ridges and intervening small valleys containing thin alluvium. Laterite caps the ridges, is present along the slopes of the ridges, and extends across the valleys beneath the alluvium. Because of conspicuous tonal contrasts, the alluvium and laterite in the ridge and valley areas are easily distinguished in the imagery. However, tonal contrasts between the alluvium and laterite are rather indistinct in the gentle flats to the east near Ouagadougou and are much more difficult to map from the imagery. Admittedly, the mapping would be facilitated by the use of a high-quality Landsat false-color composite instead of the diazochrome overlay with which the writers worked.

The writers' brief field study indicates that the alluvium in the Ouagadougou area consists of an ascending stratigraphic succession of three units referred to informally in this report as the brown, yellowish-buff, and gray alluvia on the basis of

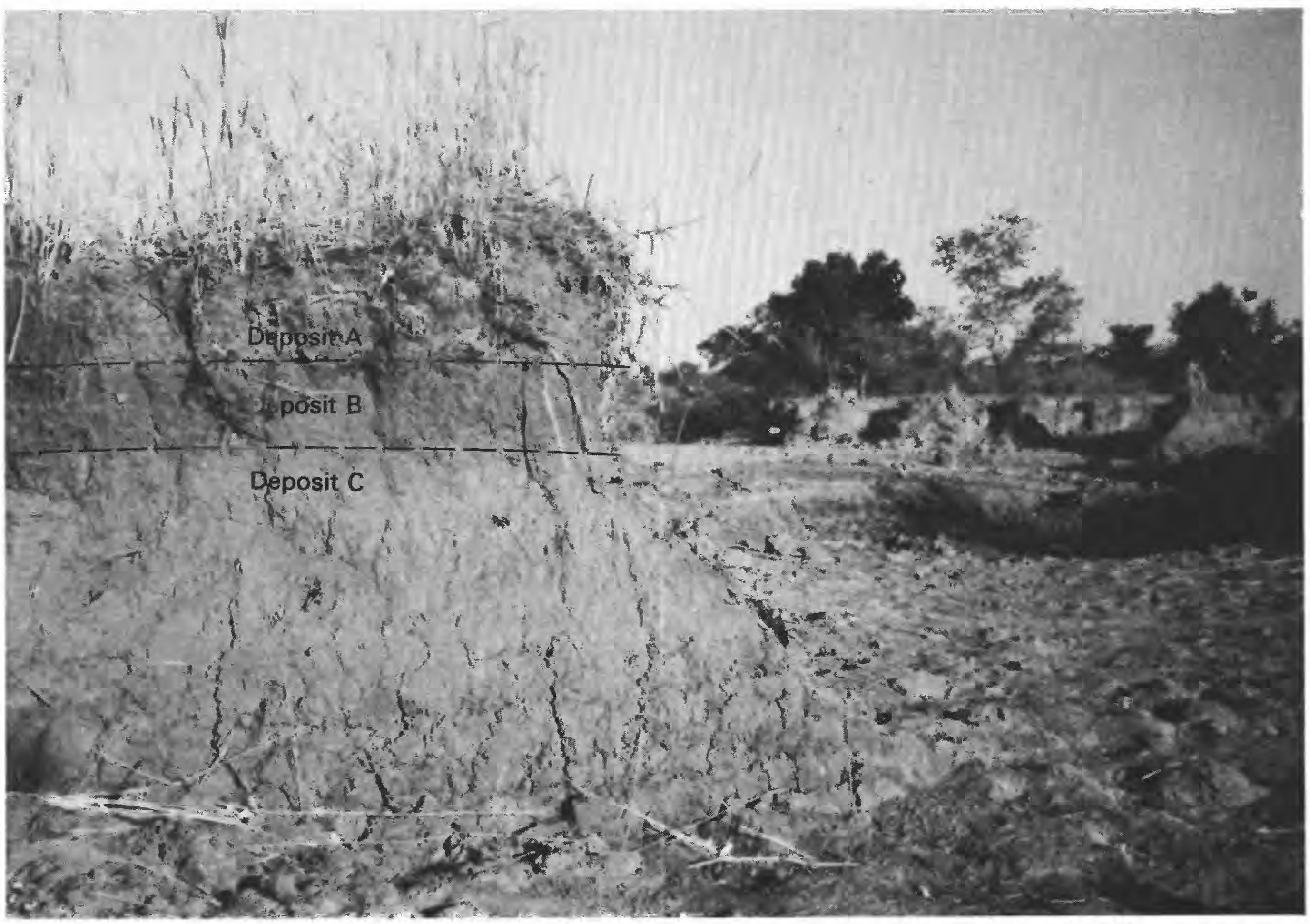


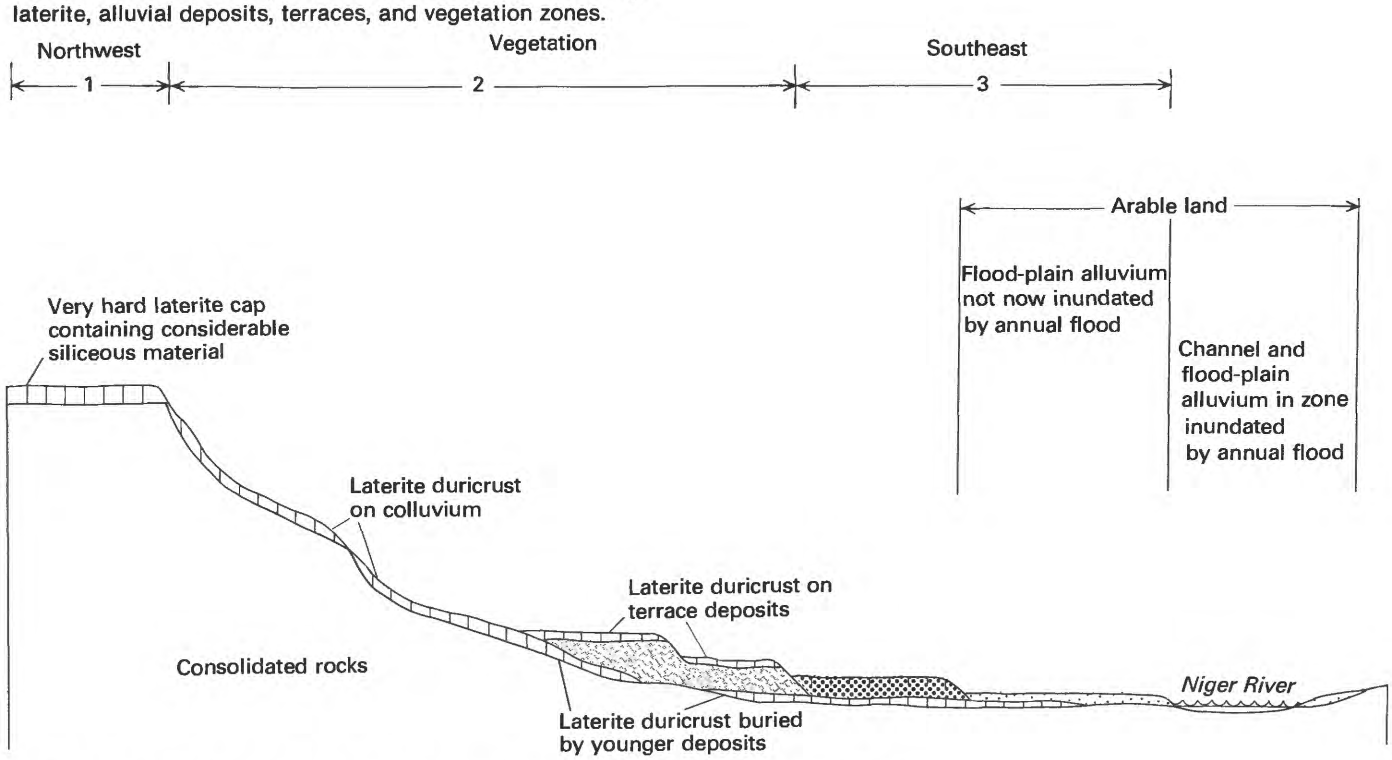
FIGURE 10.—A profile of the gray alluvium exposed in a steep-sided channel near Bamako, Mali. The upper deposit, **A**, is modern sediment deposited during floods. The middle deposit, **B**, is represented by an immature soil containing considerable plant material as indicated by the dark color. The lower deposit, **C**, is a slightly consoldiated silt to silty sand which forms the bulk of the gray alluvium. The depth of the channel is about 1.5 m. The channel shows fresh scars from recent cutting.

their characteristic colors. Where the yellowish-buff and gray alluvia are adjacent to the hard laterite, they contain only a minor amount of coarse detritus derived from the laterite. However, the brown alluvium contains a considerable amount of coarse material near outcrops of the hard laterite and basement rocks. In all localities inspected, the yellowish-buff and gray alluvia are fine grained, have seemingly consistent lithology, and show little variation in grain size. Only the gray alluvium is not altered appreciably by laterization, and it is the only one of the three types of alluvium that is arable. The other alluvia show enough laterization to preclude cultivation.

The gray alluvium, where exposed along many channels and gullies, in partially dissected flood plains near Ouagadougou and Bamako, consists of as least three deposits (fig. 10) which are separated by discrete erosion surfaces that probably represent broad channel cutting. All the deposits are fine grained, except that the uppermost, deposit **A**, laid down during the past few decades in thicknesses of 0.3 to 0.5 m, is sandier than the underlying medial deposit **B**. Deposit **B**, which generally is less than 1 m thick, consists mainly of silt and clay containing some sand and considerable organic material. It appears to represent deposition in a well-watered flood-plain environment, under somewhat moister conditions than those prevailing at present. The lower deposit, **C**, is more than 3 m thick, is slightly consolidated, and consists of layers ranging from silt to silty sand. These layers, in places, show some slight development of laterite. Along many drainageways, deposit **C** forms a low terrace a few meters high.

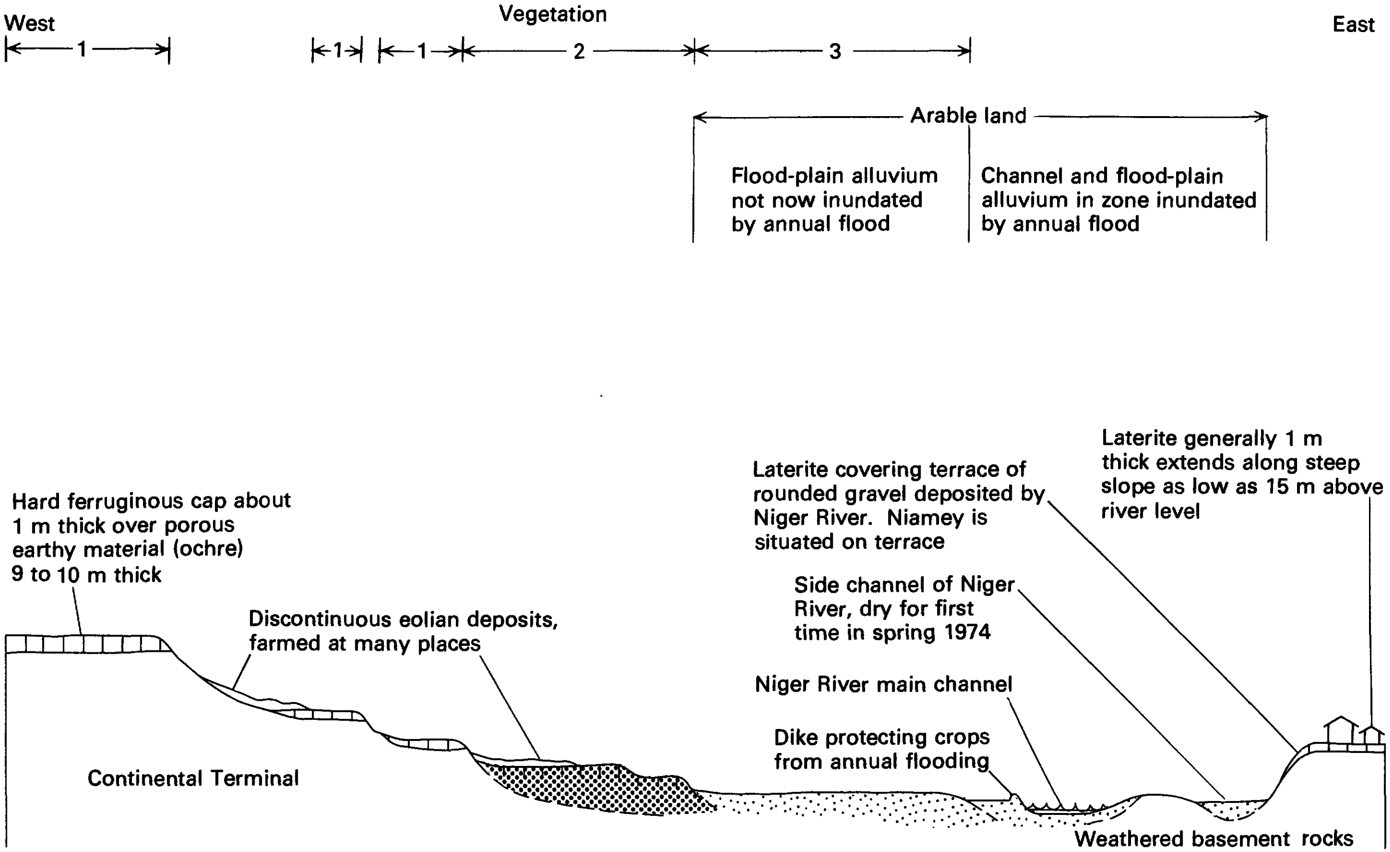
The gray and yellowish-buff alluvia and their equivalents are widely distributed in the LGA countries, but the brown alluvium was recognized only in part of the area near Ouagadougou. In contrast, deposits correlative with the gray alluvium are present as the uppermost alluvial layer in small valleys and alluvial flats throughout the region. The yellowish-buff alluvium is recognized along the White Volta, Red Volta, and other rivers in Upper Volta. Near Bamako, light-brown to yellowish-gray alluvium—believed equivalent with the yellowish-buff alluvium—occurs along the Niger River (fig. 11*A*), along the Baoulé River and in small upland valleys between these rivers (fig. 9*B*). The alluvium along these rivers forms a terrace from 3 m to about 5 m high and, except along the Niger River,

FIGURE 11.—Generalized profiles across the valley of the Niger River near Bamako, Mali, and Niamey, Niger, showing distribution of laterite, alluvial deposits, terraces, and vegetation zones.



A, Profile of the valley of the Niger River near Bamako. Maximum relief is about 175 m.

FIGURE 11.—Generalized profiles across the valley of the Niger River near Bamako, Mali, and Niamey, Niger, showing distribution of laterite, alluvial deposits, terraces, and vegetation zones—Continued.



B, Profile of the valley of the Niger River near Niamey. Maximum relief is about 100 m.

EXPLANATION

Nonarable

Arable flood-plain and channel deposits of Niger River

Equivalents of the yellowish-buff alluvium; weakly cemented laterite at top of unit

Preyellowish-buff alluvium terrace deposits

1.25 to 2 m thick

Laterite duricrust

About 10 m thick

KEY TO VEGETATION

Figure 11*A*

(1) Where soil mantle is thin, plants are confined to fractures and pockets of soil; low forest of kapok, shea butter, danya, and other trees; grasses are less prevalent than in alluvial areas.

(2) Vegetation is more dense than on alluvial flats or on mesa tops of buttes; vegetation not as tall as on the flats; trees include kapok, fig, and many others.

(3) Vegetation of areas not now cultivated in various states of recovery from farming and clearing; open forest of shea butter, locust bean, and many other trees; grasses are prevalent.

Figure 11*B*

(1) Vegetation in clumps is broken by irregular barren areas; dominant plants are drought deciduous shrubs, trees, and vines that grow about 6 m maximum height.

(2) Shrubs to 2 m high dominate; scattered doum palms and soapberry trees.

(3) Scattered baobab and mango trees on cultivated lands.

Table 3.— *Distribution of arable land and its relationship to accelerated erosion and gray alluvium*

<table>
<tr><th colspan="2">Physiographic position</th><th>Distribution of gray alluvium</th></tr>
<tr><td rowspan="3">Upland areas near Ouagadougou and Bamako</td><td>Broad flats</td><td>Forms a thin mantle on yellowish-buff alluvium and on laterite; generally is less than 1 m thick, but over wide areas is less than 0.3 m thick.</td></tr>
<tr><td>Small valleys without terraces</td><td>Forms a thin mantle on yellowish-buff alluvium; unit is greater than 1.5 m thick in central parts of valleys, but is less than 0.3 m on much of the gentle slopes along the sides of valleys.</td></tr>
<tr><td>Small valleys with terraces</td><td>Forms a generally thin somewhat discontinuous deposit on the surfaces of low terraces and on slopes behind low terraces eroded from the yellowish-buff alluvium; unit usually underlies narrow flood plains that are in front of the low terraces.</td></tr>
<tr><td colspan="2">Reaches of White Volta and Baoulé Rivers and other streams with conspicuous terraces (not including the Niger River)</td><td>Generally forms thin and discontinuous outcrops on the top of a well-developed terrace which is eroded from the yellowish-buff alluvium or its equivalents; unit underlies a narrow flood plain in front of the terraces, but, at many places, the channel occupies nearly all the bottom lands between the terraces.</td></tr>
<tr><td colspan="2">Valley of Niger River near Bamako and Niamey</td><td>Generally forms thin discontinuous outcrops on terraces eroded from the yellowish-buff alluvium and equivalents and on higher terraces and slopes; unit covers part of slopes adjacent to the flood-plain deposits of the Niger River.</td></tr>
</table>

comprises the only conspicuous terrace along these streams. The deposits along the Baoulé River may also be an upstream equivalent of sandy clays, 15 m thick along the Senegal River, described by Grove and Warren (1968, p. 196). Near Niamey, a light reddish-brown fine-grained alluvium, which is believed to be correlative with the yellowish-buff alluvium in the Ouagadougou and Bamako areas, forms terraces roughly 8 to 15 m above the Niger River. At Niamey, the upper part of this alluvium lies on rounded pebble-sized river gravels cemented by ferruginous material.

Collectively, the alluvial deposits appear light and the laterite appears dark on both Landsat black-and-white images and on false-color composites. The younger gray alluvium has a slightly lighter tone than the other alluvial units on black-and-white images and is light gray to nearly white on the color composites. Thus, its extent, which also represents the maximum extent of arable land, can be roughly delineated. Unfortunately, the scale of 1:1,000,000 is too small to permit showing the gray alluvium as a separate unit on figure S-2*B*.

In areas where the gray alluvium can be differentiated from the underlying yellowish-buff alluvium, a fair estimate of the amount and distribution of arable soil can be made, if a sufficient amount of field checking is done. Table 3 summarizes some of the relationships between the amount of arable land and different physiographic occurrences of the gray alluvium. In localities where the alluvial deposits are not easily distinguishable, only a rough estimate can be made of the distribution of arable soil. In areas where arable soil maps are unavailable, however, any maps, even if only roughly defining the areal extent of the soil, would have some value. Landsat data could be useful in the preparation of such maps.

TABLE 3.—*Distribution of arable land and its relationship to accelerated erosion and gray alluvium*—Continued

Distribution of arable land	Effects of accelerated erosion
Area favorable for cultivation may be small with respect to total area covered by the gray alluvium.	Slight sheet erosion and wind deflation around villages and in cultivated or abandoned fields.
Arable land is restricted mainly to central parts of valleys because cultivation is limited in areas where the arable soil is greater than 0.3 m thick.	Predominantly sheet erosion; severe erosion already has taken considerable land out of cultivation; locally, wind deflation is moderate.
Arable land is limited mainly to the flood plains, but part or all of the flood plains are inundated by flood flow during the rainy season; in other areas, the arable soil is too thin or discontinuous to be of much use for farming.	Sheet and gully erosion; gullying and channel dissection locally severe; sheet erosion locally severe accompanied by minor wind deflation on top of and on slopes behind the low terraces; the accelerated erosion has taken some land out of cultivation.
Little arable soil is available because of generally limited distribution of the gray alluvium; reaches of some streams such as the Baoulé River contain almost no arable soil.	Severe gullying accompanied by sheet erosion has removed much of the alluvium and locally forms sharply defined badlands.
Area of arable soil on the gray alluvium is limited, but adjacent flood-plain deposits of the Niger River are fertile and are cultivated extensively.	Sheet erosion generally slight to moderate on slopes underlain by the gray alluvium; erosion generally slight on the flood-plain deposits of the Niger River, except for some gullying along the edges of low terraces formed from these deposits.

Channel and flood-plain alluvium along the Niger River

Arable alluvial deposits in the valley of the Niger River, excluding deposits of the Inland Delta, cover thousands of hectares that are easily discerned on the Landsat imagery. The deposits comprise two broad groups: annually inundated channel and flood-plain deposits and earlier flood-plain deposits normally not flooded by the Niger River.

The first group includes silty and sandy alluvium that occurs along the channel and on adjacent flood plains within the zone covered by the annual flooding. On some of the flood plains, fields surrounded by dikes to restrain the flood water are being cultivated. In the Gao-Niamey area, the river channel is braided, consisting of a main channel with one or more subchannels. Near Bamako, the river occupies one principal channel which is flanked by broad sandy flats or beveled bedrock slopes, both nearly free of vegetation. The channels are conspicuous features on the Landsat images and are easily mapped on any transparent overlay (fig. S-4, S-5). Some farming, mainly of small vegetable gardens, is practiced along the channels during the recession of the annual flood and during the low-flow periods (fig. 12). Such farming is now minor compared to the amount that would be possible if the entire channel system was developed systematically. The small garden plots have the advantage of being easily developed without use of heavy earth-moving equipment.

The second group comprises flood-plain alluvium that forms a low terrace (or terraces) not now subject to inundation by annual flooding of the Niger River. These terraces are broad features that extend nearly continuously throughout the Gao-Niamey and Bamako areas. The fertile alluvium forming the terraces is being utilized for field cultivation and tree crops, principally mangoes, but it has the potential for more intensive development with water diverted from the nearby river. The distribution of this alluvium was successfully mapped from Landsat imagery near Niamey (fig. S-4, S-5) and Gao; its general distribution could be easily mapped from the imagery of other parts of the Niger River basin.

Laterite duricrusts

Hard reddish-brown to blackish-red laterite, in which iron oxides or hydrates are the most characteristic cementing materials (Cooke and Warren, 1973), has formed nearly everywhere in Upper Volta and in the southern parts of Niger and Mali. It is present on the summits and slopes of tablelands and ridges, on stream terraces, on gentle plains, and beneath alluvial and eolian deposits. The laterite is so prevalent that Abdoulaye Sow stated that in Mali "any well having a depth of 15 m or more penetrates laterite" (oral commun., 1974). The laterite varies widely from place to place in hardness, thickness, presence of detrital material, and composition. In places, it is thinly bedded, but, in others, it is massive. The detritus incorporated in the laterite is mainly composed of fragments of older laterite deposits, but, locally, it also includes rounded pebbles and cobbles of quartz and other dense siliceous rocks. In the areas visited by the writers, the laterite duricrust is present on Precambrian basement rocks near Ouagadougou, on Grès Ordovicien (Ordovician sandstone) near Bamako, on Continental Terminal sedimentary rocks near Niamey, on colluvium and alluvium throughout the region, and on terrace gravels of rounded siliceous pebbles transported by the Niger River near Niamey and Gao. In general, the laterite near Niamey has a greater density, presumably because of a larger amount of iron oxides or hydrates than that near Ouagadougou and Bamako.

Brief studies indicate differences in the development of the laterite duricrust on the alluvial deposits and on the terraces and slopes above the Niger River near Bamako and Niamey (fig. 13). The flood-plain alluvium of the Niger River and the gray

FIGURE 12.—Small bucket-irrigated vegetable gardens along the bank of the Niger River at Niamey, Niger.

alluvium in small valleys of the uplands do not show effects of laterization, whereas the yellowish-buff alluvium and its equivalents are associated with a slightly developed laterite that is generally weakly cemented and readily erodable. In contrast, the laterite comprising the main part of the duricrust that mantles slopes and terraces adjacent to or underlying these alluvial deposits is well indurated and is resistant to erosion. Near Bamako and Niamey, the best developed, most indurated, and thickest (about 10 m) laterite occupies the summits of the highest buttes and ridges bordering the valley of the Niger River.

The physiographic association of the different laterite deposits with buttes, ridges, tablelands, and valleys makes it possible to differentiate and to map many of the deposits by use of Landsat imagery (figs. S–1*A*, S–2*B*). The thickest and most indurated laterite generally is on the summits of topographic highs—ridges, buttes, and tablelands. These areas appear much darker on the images than the areas of laterite on the slopes of these features but not as dark as areas where the vegetation has been burned recently. The laterite areas on the slopes are partly covered by colluvium or alluvium, and, collectively, they have a reflectance intermediate between that of the dark-appearing topographic highs and the light-appearing alluvial deposits in nearby valleys.

Except for those areas underlain by consolidated rocks, all dark areas on the Landsat images that the writers studied are underlain by laterite. The dark laterite is easily distinguishable from the light tonal expanses typical of alluvial deposits but less easily distinguishable from many exposures of consolidated rocks, even if a considerable amount of ground-truth information is available. In general, the consolidated rocks are slightly lighter than the laterites but darker than the alluvial deposits. The consolidated rocks also show much more structural deformation than the laterite surfaces. Many exposures of the consolidated rocks appear to be "etched" by a pattern of closely spaced fractures. Locally, the rocks are tilted, and the tilted layers may appear as linear and arcuate patterns in Landsat images such as that showing a small area near Tombouctou (fig. S–6*A*). An intensive and detailed examination probably would reveal other diagnostic features that would aid in distinguishing the laterite from the consolidated rocks in Landsat images.

Accelerated erosion

Many of the areas underlain by alluvial deposits are undergoing severe sheet and gully erosion ac-

FIGURE 13.—Laterite in road cuts near Bamako, Mali.

A, Portion of a 10-m-thick laterite layer on the summit of a butte 175 m above the Niger River. The cut shows layering with individual layers ranging from about 1 to 30 cm thick. Some layers are very hard and contain much siliceous material.

B, Laterite formed on coarse colluvium on the slope of a butte about 20 m lower than the laterite shown in figure 13*A*. Included detritus consists of laterite fragments as much as 30 cm in diameter.

FIGURE 14.—Accelerated erosion in Mali and Upper Volta.

A, Advanced sheet erosion in the yellowish-buff alluvium near Ouagadougou, Upper Volta.

B, Accelerated erosion along stock trails resulting primarily from trampling and browsing near Bamako, Mali. Straw hat toward upper right of photograph shows scale. Photograph taken on April 25, 1974, near the end of the 1973–74 dry season.

C, Steep-sided channel (similar to arroyos trenched along many drainages in Southwestern United States) about 1.5 m deep cut in soft alluvium. Scour in channel forms a temporary water hole. Picture taken east of Ouagadougou, Upper Volta, on May 13, 1974, near the beginning of the rainy season.

companied by wind deflation. This erosion unfortunately has resulted in the irreplaceable loss of much fertile soil (figs. 6*B*, 10, 14) and already has taken from production considerable tracts of cropland and rangeland. The principal areas of accelerated erosion lie in small valleys of the upland regions and along stretches of the larger rivers. The use of Landsat imagery for identifying such severely eroded areas (fig. S-2*C*) is an important tool in analyzing environmental problems confronting the LGA countries.

Gentle slopes of small valleys without terraces (fig. 9*A*; table 3) have been subjected to severe sheet erosion during the past several decades. The sheet erosion has removed much of the most fertile part of the gray alluvium. In places, erosion has removed this alluvium altogether, thereby enlarging the exposures of the nonarable deposits. Man's activities, especially near the villages, have aided and accelerated the erosion by destroying the natural vegetation through excessive grazing, trampling (fig. 14*B*), cultivation, and bush burning. The removal of the vegetation aids wind deflation which is manifested by accumulations of dust around small clumps of brushy vegetation growing on the nearby slopes and ridges underlain by laterite.

In the well-drained terraced valleys (figs. 9*B*, 14*A*, table 3), gully and sheet erosion takes place on the slopes of the valleys and along stream channels and low terraces toward the centers of the valleys. At many places near Ouagadougou and Bamako, the valleys are in the process of being deepened by downcutting (figs. 10, 14*C*). These large gullies and steep-sided channels are similar to the perpendicular walled arroyos or channels formed since about 1870 along many drainages in the Southwestern United States. The new channels display freshly cut scars, most ranging in depth from 1.5 to 2 m. Generally, the channels are discontinuous and, fortunately, have not yet caused extensive damage to cultivated land. The channel downcutting would be more extensive if it were not for low stream gradients which tend to retard and localize the process. At places near Niamey, gullies and well-developed vertical walled channels are present along the sides of the Niger River valley. In this vicinity, the channels have been readily incised in loose sandy alluvial deposits.

Many areas of badlands, scored by severe gully erosion, border the White Volta, the Baoulé, and other rivers in southern Mali and Upper Volta and are present at places near the Niger River in Niger. Groups of headward-cutting gullies are advancing into terraces and slopes formed principally of the easily erodible yellowish-buff alluvium and its equivalents. In places, the terraces have been nearly obliterated by the gullying. In most places, severe sheet erosion accompanies the gullying.

The areas of accelerated erosion are large enough to be easily identified on black-and-white Landsat images or on false-color composites (figs. S-1*A*, S-2*C*). The color composites enhance the contrast between the severely and slightly eroded areas, thereby facilitating their mapping. From on-site inspection, the writers observed that the lightest areas on the images, appearing as "bright" areas within alluvium, indicate severe erosional activity. The bright areas generally appear as spots or blotches or combine in a somewhat elongate or linear pattern along the eroded edges of terraces.

Annual flood of the Niger River

The Niger River, the lifeline of Mali, Niger, and much of Nigeria, heads in the highlands of Guinea and the Ivory Coast. Its flow is sustained by precipitation that occurs only during the rainy high-sun months (May–October). The river flows through a wide plain stretching from Mopti to the Detroit Soudanis (Sudanese Narrows) near Gao. This plain of low relief is laced with waterways and is called the Inland Delta of the Niger. The Niger River within the Inland Delta includes a main channel and many anastomosing distributary channels (fig. S-6*A*), some of which carry water only during high flows. Near Tombouctou, several distributary or overflow channels extend northward and terminate in a maze of active sand dunes along the southern margin of the Sahara (fig. S-6*B*). Throughout the centuries, the shifting of floodwaters in these distributaries has determined where people live and the use they made of the land in the Inland Delta.

The flow of the Niger River is sustained during the long dry season (10 months at Tombouctou) by the precipitation that fell during the previous rainy season. Part of this precipitation does not run off immediately and is not evaporated but directly infiltrates the land surface to recharge the ground-water reservoir. Another important recharge to the ground-water reservoir occurs during the annual flood when large areas are inundated by the Niger for weeks at a time. Slow drainage from the ground-water reservoir helps maintain the river's flow during the dry season. The time of minimum flow of the river is in April at Bamako and in June at Niamey. From 1954 to 1972, the mean annual discharge ranged from a high of 2,063 cubic meters per second in 1969 to a low of 1,083 m^3/s in 1972 (table 4). Beginning in 1970, the mean annual flow of the river has been consistently lower, a manifestation of the major drought cycle that has affected much of Sub-Saharan Africa for the past 5 years.

The Niger River has a large annual flood that moves slowly downstream and takes several months to travel from Bamako to Gao, an airline distance of about 1,300 km. The crest of the 1972–73 annual flood after the 1972 rainy season passed Bamako in September, Mopti in October, Tombouctou at the end of November and the beginning of December, and Gao near the end of December 1972 (data from RAF/71-1283, Flood and Drought Forecasting and Warning System in the

TABLE 4.—*Mean annual discharge at two gaging stations in the Niger River System, southern Mali*

[Data from RAF/71-1283, Flood and Drought Forecasting and Warning System in the Niger River Basin, World Meteorological Organization, Bamako, Mali]

Year	Mean annual discharge (cubic meters per second)	
	Niger River at Bamako	Bani River at Mopti
1972	1,083	694
1971	1,261	1,196
1970	1,157	1,139
1969	2,063	1,620
1968	1,459	1,173
1967	1,912	1,333
1966	1,438	1,472
1965	1,502	1,316
1964	1,566	1,622
1963	1,559	1,328
1962	1,832	1,617
1961	1,275	1,194
1960	1,657	1,250
1959	1,539	1,284
1958	1,502	1,483
1957	1,978	1,427
1956	1,365	1,264
1955	1,981	1,693
1954	1,969	1,636

Niger River Basin, World Meteorological Organization, Bamako, Mali). The progress of the flood crest is especially slow through the Inland Delta where the waters spread across an area about 100 km wide.

Many investigators familiar with the Niger River have suggested that its annual flood could be monitored by the use of the Landsat imagery. Figure S-6*A* was prepared to show the feasibility of monitoring and mapping the annual flood from images. This image shows part of the Inland Delta near Tombouctou and the extent of the flood on October 12, 1972, a few weeks before the maximum flood stage or extent in this area.

Ground-water development in fractured rocks

Many consolidated rock terrains in the LGA region are crisscrossed by extensive networks of linear features that can be mapped from aerial photographs as well as from Landsat imagery (fig. S-1*B*). These linear features indicate that the rocks are fractured intensively in places, such as at the intersections of the main linear features. In such places, the consolidated rocks may have a sufficient secondary permeability to contain dependable supplies of ground water that could be tapped by drilled wells.

In the area shown on figure S-1 of Bamako vicinity, the consolidated rocks are composed mainly of tightly cemented sandstone referred to by Archambault (1960) as the Grès Ordovicien (table 1). These rocks are nearly horizontal or dip gently to the north and northeast. Some of the sandstone members contain a few rounded quartz pebbles, and, at one exposure about 48 km north of Bamako on the road leading to Didieni, the sandstone contains some coarse pebble conglomerate. At Bamako, part of the sandstone shows some ripple marks and well-formed generally medium-scale current-bedding dipping to the east and northeast that indicates that it was laid down in generally eastward-flowing streams. At Koulikoro, a sandstone member that also has east-dipping current beds and that probably is the same unit as the one at Bamako is exposed at the base of a high bluff. Above this sandstone member is another sandstone that has large-scale high-angle crossbedding dipping westward. The crossbedding and the generally uniform fine to medium grain size suggest that the sandstone was deposited by winds blowing generally from the east.

Yields of wells penetrating the relatively unfractured parts of the Grès Ordovicien probably would be small at best and sufficient only for supplying stock and small villages, but the yields of wells drilled into the fractured zones of the sandstone would be considerable and perhaps could supply comparatively large communities with water. Evidence that fractures locally influence the occurrence and movement of ground water is demonstrated in two ravines at Bamako. Ground water discharging from fractures in the sandstone sustains springs in the Ledo Canyon ravine and, as recently as 20 years ago, sustained a small flow in the shallow ravine near the Bamako Zoo (Abdoulaye Sow, oral commun., 1974).

Storage and movement of ground water is clearly indicated along the large linear features in the Baoulé River area northwest of Bamako (northwestern part of fig. S-1*B*). The writers inspected this area from a light plane flying less than 200 m above land surface on May 2, 1974, near the end of the 1973–74 dry season. The specific trace of some of the linear features was observed to extend for more than 30 km. Differential erosion of the fractured rocks along the linear features has carved small narrow somewhat wedge-shaped canyons along the edges of buttes and ridges. At other places that have a gentle topography, many of the linear features support a growth of vegetation denser than that on the relatively unfractured rocks away from these features (fig. 15). Patches of verdant vegetation were observed at intersections of the large linear features. Inspection from the air disclosed that the channel of the Baoulé River above its confluence with the Bakoye River in the area of Parc National de la Boucle de Baoulé contains large pools of water and short reaches of seemingly perennial flow downstream from the points where the river crosses large linear features; the other reaches of the river were dry at this time. As far as could be ascertained from air reconnaissance, the water in the river's channel is maintained by the discharge of ground water from the fractured rocks along linear features.

Landsat images are especially useful for mapping the main linear features (fig. S-1*B*). In areas of high relief, where differential erosion of the rocks is great, the linear pattern is easily discerned, but, in other areas, such as plains underlain by laterite, lineation is much fainter. The linear network provides a key to fracture trends and thus to the possible paths of ground-water movement in the consolidated rocks. Study of the lineations may point to favorable places where ground-water supplies in the consolidated rocks could be developed. Most favorable places would be along lineations representing fractured zones and especially at points of intersecting lineations.

FIGURE 15.—Low-altitude oblique aerial photograph showing fractures, indicated by arrows, in the Grès Ordovicien (Ordivician sandstone) near the Baoulé River northwest of Bamako, Mali. The photograph was taken from a light aircraft on May 2, 1974, near the end of the 1973–74 dry season. Dense vegetation in the niche carved in the large fracture suggests presence of permanent ground water at shallow depth.

Evaluation and Utilization of Landsat Imagery

Landsat imagery provides a valuable source of information required for solving important resource problems of the developing countries in semiarid and arid regions. It displays a view that is unique in its comprehensiveness and its repeatability and gives a quick, convenient, and inexpensive means of examining the Earth's surface—a means that otherwise is not available to investigators and planners in the Sahelian countries. In essence, the imagery extends the vision of the investigator or planner by furnishing him a synoptic picture of the terrain, drainage network, vegetation, and geohydrology of a particular region. Given this general framework of information, the investigator may then choose, if warranted, more detailed methods of examination. Proper interpretation of the imagery depends, in considerable measure, upon adequate onsite verification and upon the investigator's knowledge and experience in dealing with environmental problems. An important attribute of the imagery is its simplicity—interpretation of the imagery does not require sophisticated photogrammetric equipment or specially trained photointerpreters.

As with any remote-sensing technique, the use of Landsat imagery has certain limitations imposed by environmental conditions. The most commonly encountered conditions in West Africa that impose such limitations are as follows:

1. The general evenness of the West African landscape and the lack of sharp tonal contrast in the imagery limit the usefulness of the imagery for mapping detail, even with excellent ground control.
2. The imagery provides a view of the land surface only; thus, surficial features such as the widespread laterite duricrust or dune-sand

mantles may conceal the underlying rocks and obscure many geohydrologic details.

3. Activities of man such as clearing, overgrazing, bush burning, cultivation of fields, and construction near villages may obscure natural vegetative and geohydrologic boundaries.
4. In West Africa, the widespread atmospheric haze that is present during much of the dry season hampers Earth-observation studies to some extent. During the rainy season, extensive cloud cover poses an additional problem.

In spite of these limitations, the imagery can be usefully applied (1) to provide a general overview of a region as well as to serve as base maps in regions where few or no good ground surveys exist, (2) to provide a method for surveying, cataloging, and mapping Earth-resources information, (3) to provide a basis for repetitive inventorying and monitoring transient environmental changes, and (4) to aid in solving special problems of disease-vector control or human activity.

The Landsat images give an excellent visual impression of the landscape, including cultural and environmental features. The images can be grouped in mosaics to provide broad regional or national coverage. Such image maps can be effectively used as base maps showing the major drainage systems and reservoirs and the location and areal distribution of other natural and cultural features.

Landsat images give excellent synoptic views of faults, fractures, and other linear geologic features and of the lithologies of older consolidated sedimentary and basement rocks, where they are exposed. Because of the concealment of these rocks in much of the LGA region and of the generally low relief, the Landsat images are more applicable to mapping of younger surficial deposits. Accompanied by onsite investigation, the images form an excellent means for preparing small-scale maps showing flood plains, dunes, alluvial deposits, laterite duricrust, and accelerated sheet and gully erosion. Areas of arable land can also be determined because of the association of such areas with certain alluvial deposits. In some of the LGA countries, such as parts of Niger, where accurate and complete geologic maps are available, relatively little new information concerning rock distribution or composition will probably be obtained from the imagery. Nevertheless, in most places, regardless of the previous geologic map coverage, analysis of the imagery can contribute to the knowledge of the details of geologic features previously identified by conventional methods. When identified in the imagery, these features provide additional insight into the broad geologic configuration of the region.

Landsat imagery can be used directly and indirectly to examine hydrologic features of the Sahel. Streams, lakes, and reservoirs are examples of directly observed features. Other features can be largely inferred from the vegetation or geology. Some hydrologic features that may be indentified indirectly include presumed permeable zones along the main linear structural features and at the points of intersection of these features, areas of shallow ground water in flood plains and in dallols (ancient drainages, fig. 16), and sites suitable for surface-water storage or for catchments.

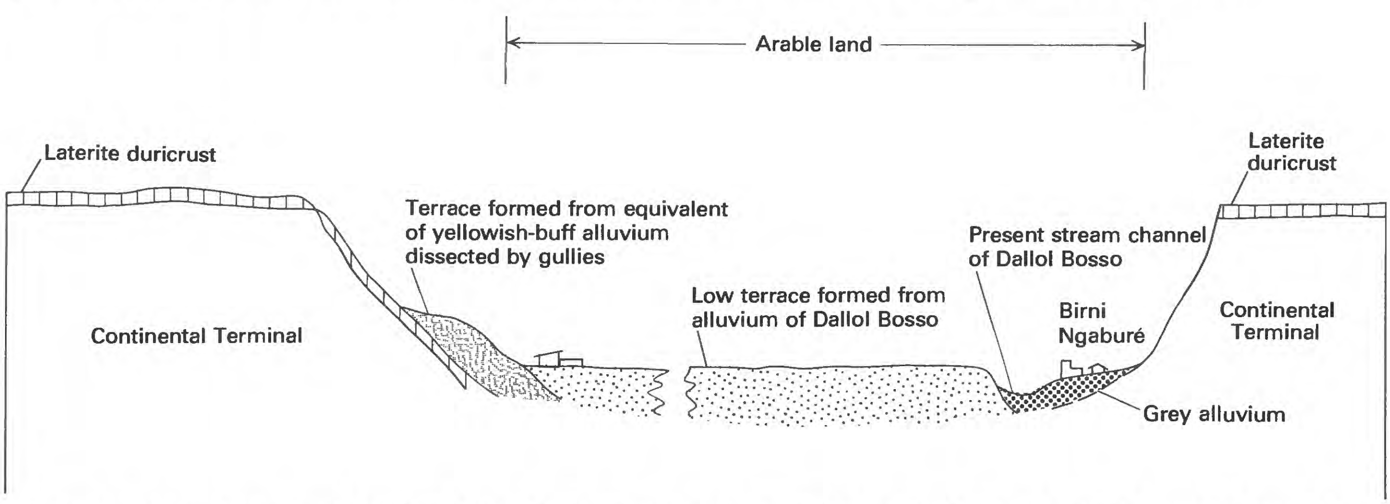


FIGURE 16.—Diagrammatic cross section of Dallol Bosso near Niamey, Niger. The length of section is about 7 km. The width of alluvium of Dallol Bosso is about 5 km. This section shows about 100 m of vertical relief. Because of almost complete cultivation, the floor of the Dallol Bosso near Birni-Ngaburé supports only scattered trees that have been preserved in the clearing process. Prominent among these trees are the doum palm and the baobab tree. The uplands, only sparsely cultivated because of laterite duricrust, support an open forest of varying composition depending upon soils and history of burning and clearing.

Many transient environmental features showing seasonal change can be observed with repetitive Landsat imagery. These features are principally vegetative, but they may have hydrologic implications. Seasonal change in foliation of vegetation is a commonly observed phenomenon on Landsat imagery. Seasonal differences are especially marked in regions that have fluctuating rainfall and temperatures. The use of Landsat imagery to measure regional crop yields during the early part of the rainy season is probably one of the most important applications.

Transient hydrologic phenomena such as the stages of rivers in floods or at low flow, intermittent streams, fluctuating lake levels, reservoirs, or small ponds can all be identified and their general stages monitored by repetitive imagery. The annual floods of the Niger, Senegal, and Volta Rivers and their larger tributaries should be rather easy to follow as the floods progress slowly downstream. Within the Inland Delta of the Niger River, knowledge of the exact area inundated by floodwater would be important information upon which to base yield estimates for crops grown after the flood.

Repetitive imagery may help locate shallow ground-water bodies that could provide a water supply during part of the dry season. Patches of lush vegetation often indicate areas of shallow ground water, particularly along intermittent streams and in small alluviated valleys, where ground water is discharged. All dark spots or areas shown on bands 6 and 7 of Landsat imagery are worth checking to determine if they are "damp" areas, where the water table is near the land surface, or ephemeral lakes or ponds that may not be related to the presence or discharge of ground water.

Landsat imagery can be used to assist in disease-vector control programs such as the tsetse fly and river-blindness control programs.

Landsat Imagery With Explanations

The following section presents analysis of six Landsat images S-1 to S-6 (fig. 17). The analyses of two images were originally made on false-color composites of multispectral scanner (MSS) bands 4, 5, and 7 prepared at the EROS Data Center, but the analyses of the remaining four images were made by using diazochrome overlays for which band 4 was reproduced in yellow, band 5 in magenta, and band 7 in cyan. Comparisons also were made between the false-color composites or diazochrome overlays and the black-and-white frames of all four MSS bands.

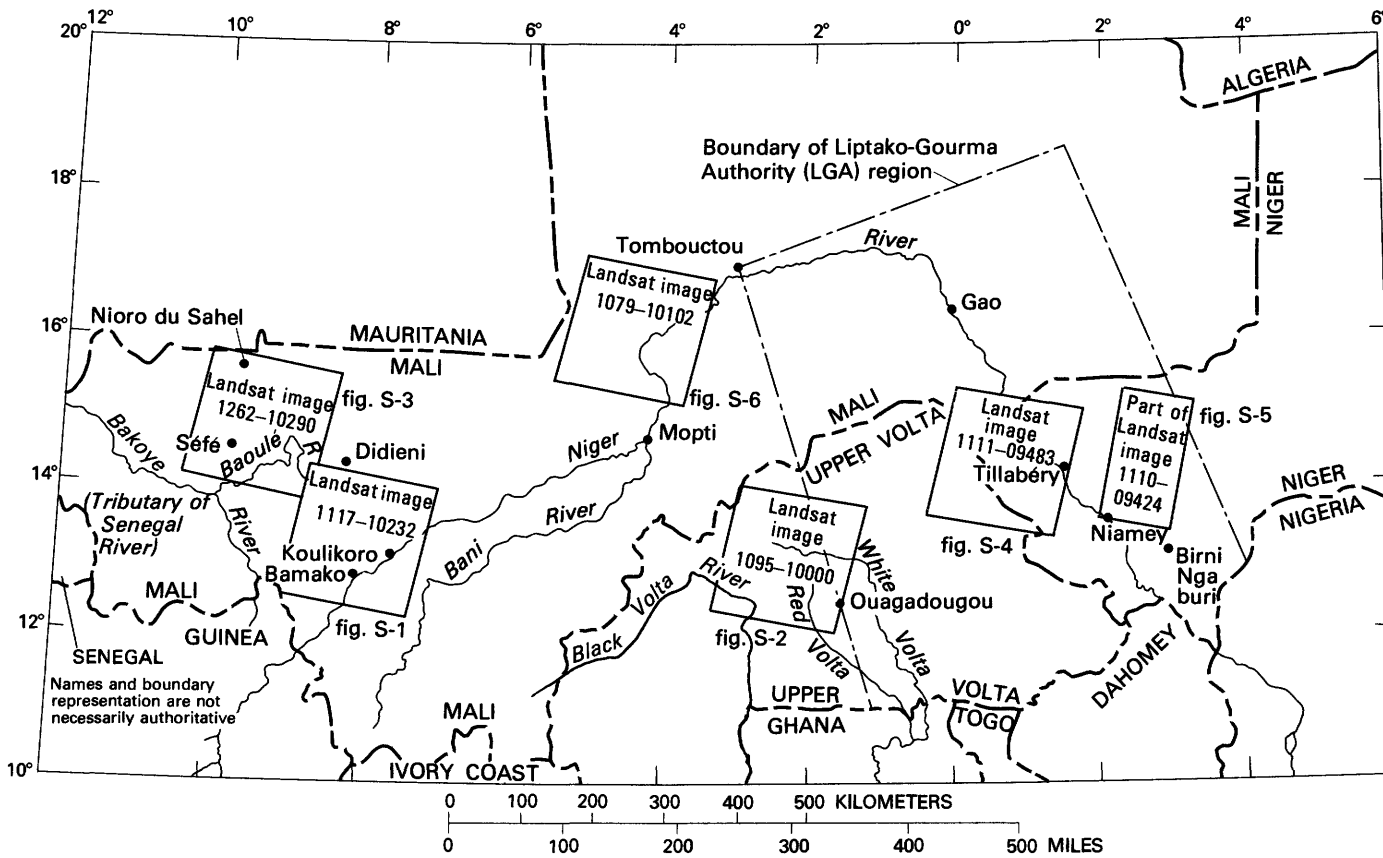


FIGURE 17.—Areas represented by the six selected Landsat images of Mali, Niger, and Upper Volta that are evaluated in this report.

FIGURE S-1.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1117-10232, November 17, 1972) showing the region near Bamako, Mali. This image shows an excellent panorama of the geohydrologic setting; the drainage network, including the Niger River valley and adjoining ridges and buttes; the vegetation; and many features of the small valleys and alluvial flats. (Approximate scale is 1:1,000,000.)

FIGURE S–1.—False-color composite Landsat images (MSS bands 4, 5, and 7 of 1117–10232, November 17, 1972) showing the region near Bamako, Mali. This image shows an excellent panorama of the geohydrologic setting; the drainage network, including the Niger River valley and adjoining ridges and buttes; the vegetation; and many features of the small valleys and alluvial flats—Continued.
(Approximate scale is 1:1,000,000.)

EXPLANATION S–1*A*

This overlay shows the general distribution of laterite, alluvium, and areas of accelerated erosion (see arrows and also figure S–2) and illustrates how the imagery can aid the tse-tse fly control program.

Alluvial deposits (the gray alluvium and equivalents of the yellowish-buff alluvium) constitute the light areas of the image. In well-drained valleys, the gray alluvium occupies narrow flood plains and appears as a reddish-brown band of vegetation. The lightest areas are those alluvial areas undergoing accelerated erosion. The laterite-capped buttes and ridges and the indurated Ordovician (Grès Ordovicien) sandstone that form these features appear dark. Laterite, partly covered by thin alluvial deposits on slopes and in areas of low relief, has an intermediate tone. The irregular dark areas, showing little relation to the topography, are burned areas.

Tse-tse flies require shade during the warm part of the day and seem to prefer large clumps of trees or continuous forest rather than individual trees. Toward the northern edge of the fly's range, dense groves of trees large enough to support tse-tse populations occur only in special habitats. In the Bamako area, one such habitat of dense groves is along the flanks of laterite-capped mesas. Here one might expect isolated pockets of tse-tse flies. Toward the lower left corner of the image, in an area where rainfall probably reaches a maximum for the area of the frame, some of the buttes attain altitudes of more than 650 m. Hillslope forests, which developed because of the greater rainfall of these elevated lands, are possible habitats of tse-tse flies and appear as thin red patches fringing the elevated laterite-capped summit areas (see arrows). In the vicinity of Bamako and northward, where altitudes are 250 to 300 m lower, the hillslope forests are not developed.

EXPLANATION S–1*B*

Landsat imagery is extremely useful for mapping linear structural features. This overlay shows the linear features that may affect the movement and storage of ground water in the consolidated rocks (Grès Ordovicien) near Bamako. The linear features, indicating to a large extent valleys, drainage lines, and ridges, trend as straight or slightly curved lines.

——— — — — — Major linear structural features

— — — — — — — Minor linear structural features

Intersections of the major linear structures seem to be the most promising places for obtaining adequate ground-water supplies from deeply drilled wells.

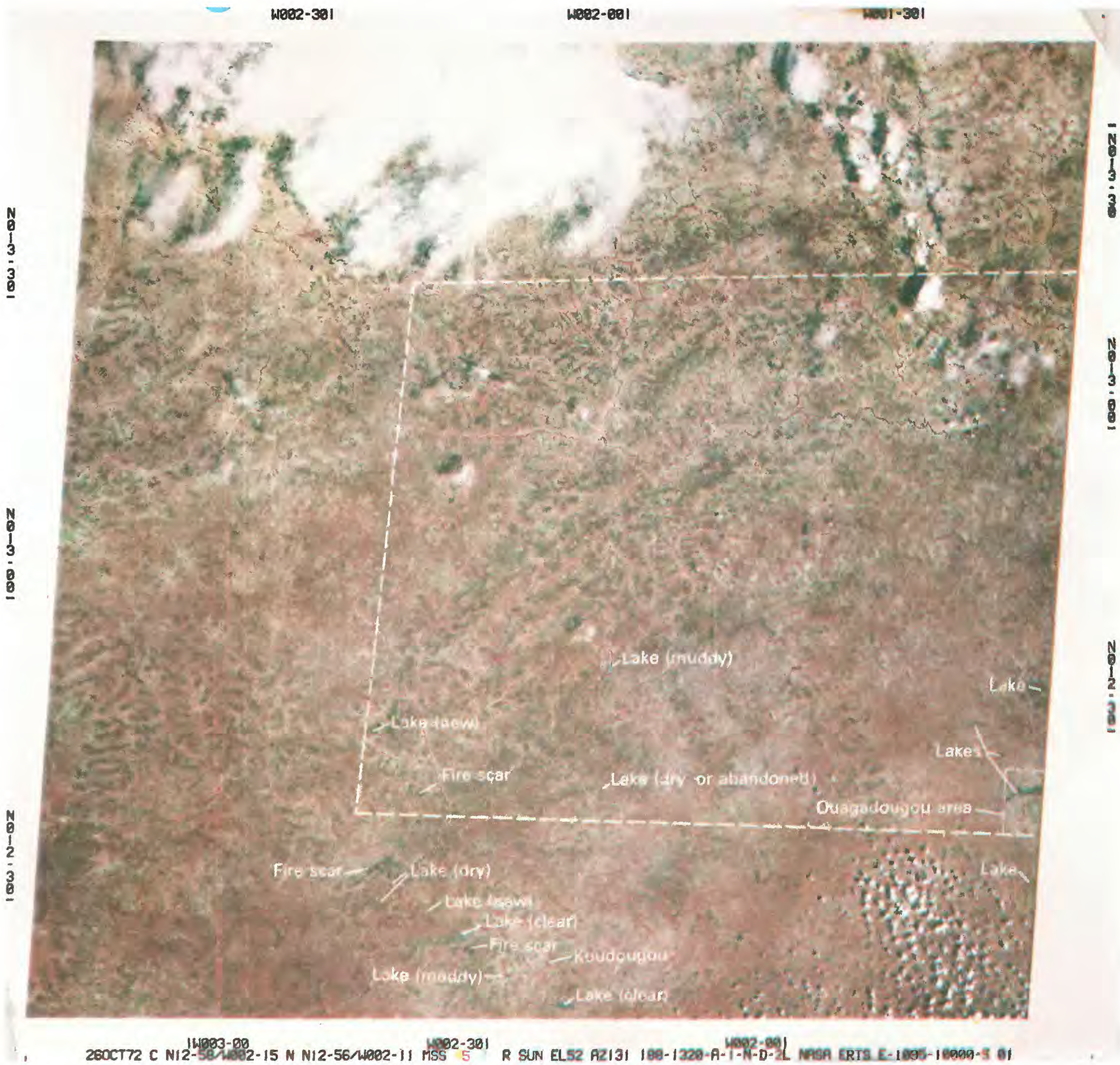


Figure S-2.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1095-10000, October 28, 1972) showing the area near Ouagadougou, Upper Volta. This image was used to map lakes, reservoirs, laterite, alluvium, and areas of accelerated erosion. (Approximate scale is 1:1,000,000.)

EXPLANATION S–2*A*

In the southern part of image 1095–10000, several lakes or reservoirs appear blue, if muddy, and dark purple, if clear. Several lakes shown on a map of the area (Army Map Service map 1501XND3015; ground-checked from 1959 to 1964; scale 1:250,000) are not visible on the Landsat image, presumably because they were dry at the time of the satellite overpass. Other lakes seen on the image but absent from the map are presumably new or were missed at the time ground-checking for the map was done. To be visible on Landsat images, a lake must be more than about 250 m in diameter. Some of the lakes are ringed by white, indicating that grazing and erosion are probably severe near the lake. The large lake near Ouagadougou does not have a white ring because of the dense vegetation that grows along its shore.

Spillways for lakes such as those seen on this image may be breeding sites for the fly, *Simulium damnosum*, which carries river-blindness disease (Tomiche, 1974). Because these bodies of water are often temporary and because new stock ponds are constantly being constructed, as for example, in a Peace Corps program in Upper Volta, Landsat imagery could serve as a means for locating these sites, which are potential loci for the spread of river blindness.

The tonal contract between the laterite and alluvium is excellent in the northwestern two-thirds of the image where the land has moderate relief. In the area of low relief in the southeastern part of the image near Ouagadougou, the contrast is poor, making differentiation between the areas underlain by laterite or alluvium difficult to discern with either the black-and-white images or with the false-color composite. Areas of low relief may be beyond the limit of Landsat capabilities because of the slight tonal differences in soil-surface color occurring there.

The laterite appears dark on the false-color composite or on the black-and-white bands, of which MSS band 7 is the most useful for distinguishing the laterite from the alluvium. The areas underlain by alluvium appear as different light tones, depending upon the amount of vegetation, the amount of foliage at the time of the overpass, the amount of accelerated erosion, and the distribution of the different alluvial deposits. The gray alluvium appears slightly lighter than the other alluvial deposits, but not as light where it or the other deposits are being subjected to accelerated erosion.

Several recently burned areas are visible as dark splotches on the image. These splotches may be distinguished from clear lakes because the burned areas appear less blue and are not confined to low positions in the terrain. (See also figure S–3.)

The area underlain by the gray alluvium represents the only available arable land. In much of this area, however, the gray alluvium is too thin for extensive cultivation (table 3), partly as a result of accelerated erosion. The general distribution of the gray alluvium and of the arable land can be coarsely outlined from this image. In valleys where the gray alluvium underlies a narrow flood plain along the main streams and is subjacent to terraces formed from the yellowish-buff alluvium, the flood plain may support relatively lush vegetation that appears dark on MSS band 5 and reddish-brown on the false-color composite. In the alluvial flats and in valleys lacking terraces, the gray alluvium extends nearly across the alluviated area.

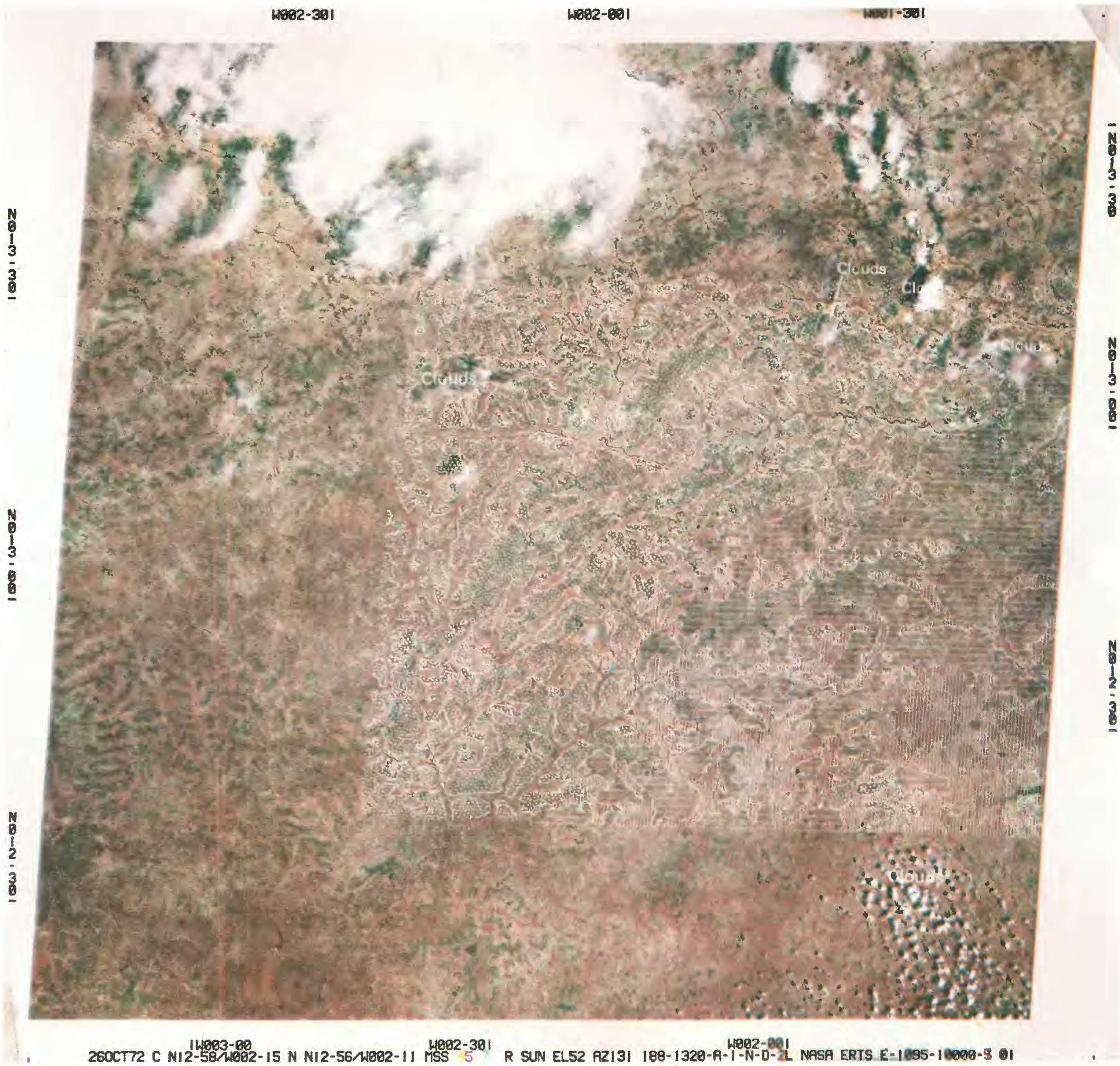
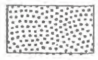


FIGURE S–2.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1095–10000, October 28, 1972) showing the area near Ouagadougou, Upper Volta. This image was used to map lakes, reservoirs, laterite, alluvium, and areas of accelerated erosion—Continued. (Approximate scale is 1:1,000,000.)

EXPLANATION S–2*B*

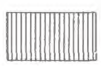
Figure S–2*A* shows the preliminary results of mapping of the laterite and alluvial deposits in a moderately to slightly dissected region shown in the east-central part of this image.



Area underlain chiefly by laterite duricrust generally more than 2 m thick on summits of low narrow mesas and ridges and on their slopes. Most mesas and ridges are too small for the laterite on their summits to be separated from that on their slopes.

Area underlain chiefly by the brown, yellowish-buff, and gray alluvia. Includes small outcrops of laterite too small to show separately.

Area consisting of gentle slopes underlain by laterite duricrust and alluvial flats and valleys underlain by the brown, yellowish-buff, and gray alluvia. Locally, the alluvial deposits may exceed 25 percent of the total area. The outcrops of laterite and alluvia are too small or too irregular to show separately at this scale.



Gentle plain near Ouagadougou underlain by laterite duricrust and thin alluvium consisting of the brown, yellowish-buff, and gray alluvia. Although the gray alluvium may cover more than 50 percent of the area, the deposit is as thin as 20 cm thick in some places.

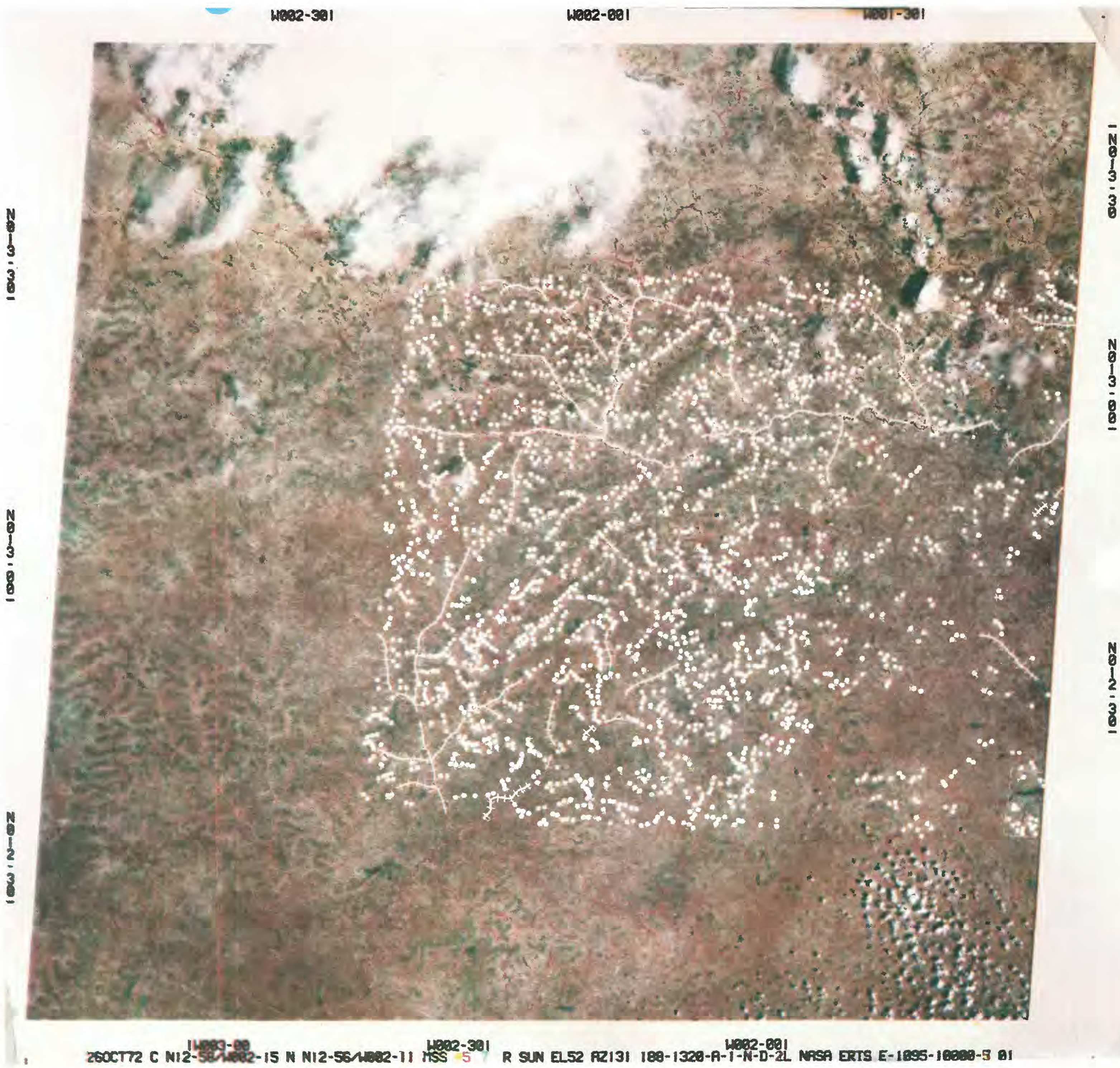


FIGURE S–2.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1095–10000, October 28, 1972) showing the area near Ouagadougou, Upper Volta. This image was used to map lakes, reservoirs, laterite, alluvium, and areas of accelerated erosion—Continued. (Approximate scale is 1:1,000,000.)

EXPLANATION S–2*C*

Areas of accelerated erosion can be recognized easily on the Landsat black-and-white images or false-color composites.

Dots represent areas undergoing severe sheet erosion. Includes small areas of headward gullying along terraces of the larger streams and areas of scattered severely sheet-eroded alluvium overlying laterite, both of which are too small to be shown at this scale.

Area of extensive headward gullying along channels and along terraces formed from the yellowish-buff alluvium.

On this image, areas of accelerated erosion have the greatest reflectance and appear as light spots, white splotches, or as features that are irregular, somewhat elongated, or linear. The linear or elongate features represent areas of severe sheet and gully erosion along terraces, whereas the other features are principally areas of severe sheet erosion. The width, depth, or the distribution of the gullies cannot be determined from the Landsat images and must be obtained from onsite inspections or from large-scale aerial photographs.

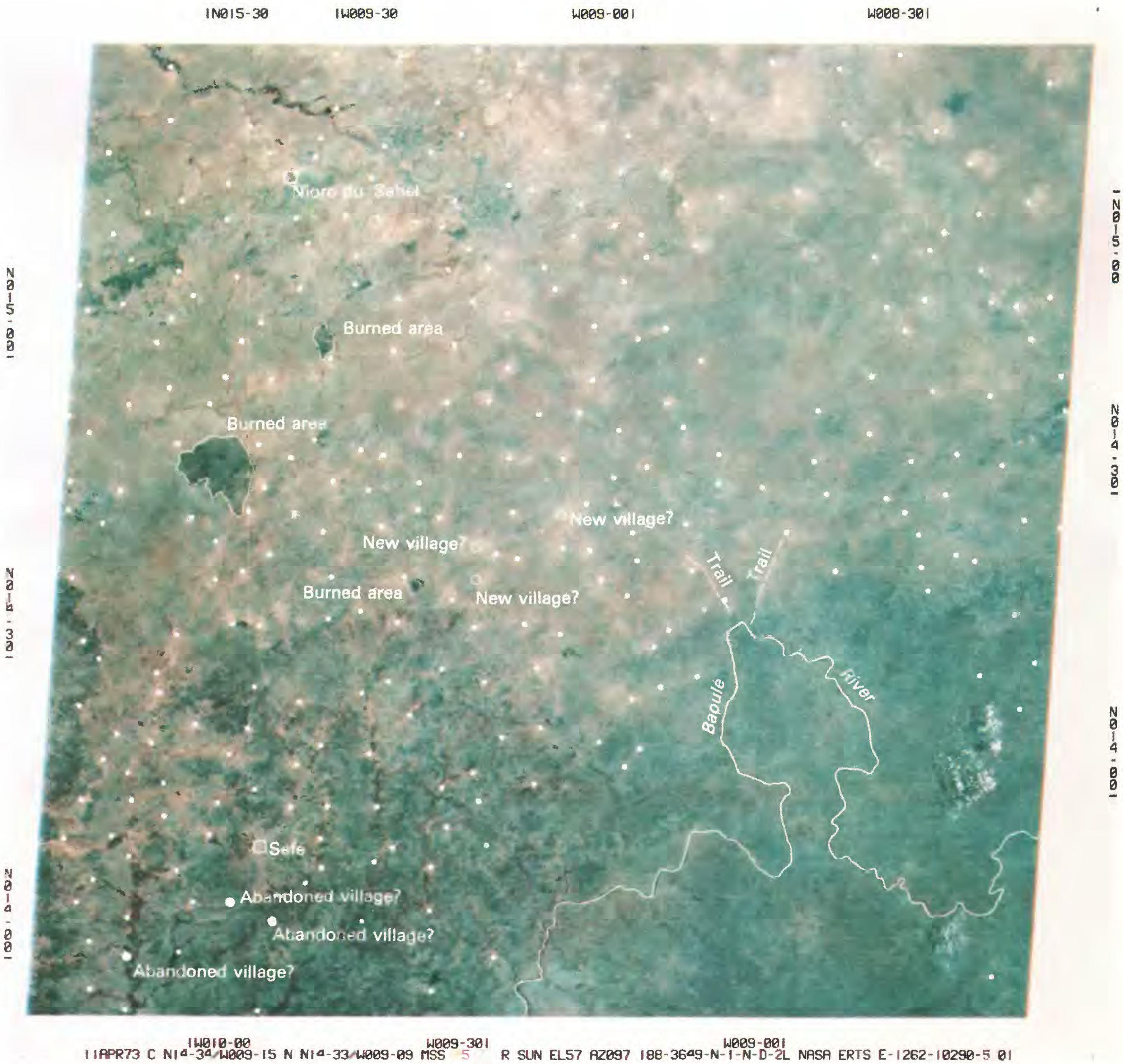


FIGURE S-3.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1262–10290, April 11, 1973) showing the Baoulé River country northwest of Bamako, Mali. The image shows burned areas and the distribution of villages. (Approximate scale is 1:1,000,000.)

EXPLANATION S–3

Villages can be seen easily on this Landsat image, which shows the region near Nioro du Sahel and Séfé, Mali. The light areas are land from which much of the vegetation has been removed by farming and grazing. These denuded areas reflect light throughout all spectral bands to which Landsat is sensitive. Villages are usually somewhere within the denuded areas. Some trails also appear as light-colored strips, presumably because the vegetation along them has been thinned out. To verify that the pattern of light spots seen in the image is produced by villages, a map of all villages within the area shown in this image was drawn from Army Map Service map 130XND29 (scale 1:1,000,000). When compared with the Landsat image, the correspondence between the location of the villages shown on the map and light areas in the image is close, although several villages not on the map appear in the image. Conversely, several villages noted on the map appear from their appearance on the image to have been abandoned.

Several large dark areas seen in this image were not in an August 1973 image 1028–10274 (not shown). Although the writers did not visit these areas, they are probably the result of bush fires. In comparing the April 11, 1973, image to an April 29, 1973, image (not shown), additional dark spots were found in the latter image. These spots are presumably areas which were burned over in the 18-day period between the two satellite overpasses.

If attempts are made to limit bushburning or to limit it to a given season, Landsat imagery could be used to detect and monitor fires. North of the area shown in this image, bushburning is forbidden by law in some places, and satellite imagery could be used to aid in administering the bushburning supression policy there.

The Baoulé River is barely visible in this image, and inspection of the area revealed the reason. This, and many other streams in the area, lack the fringing forest that is typical of watercourses in the Sahara and other deserts of the world. Instead of a concentration of these typical plants, streamcourses in this region support vegetation that is little different from the vegetation of the surrounding area. As a consequence, the streams are not accentuated on Landsat images and are difficult to detect. The absence of a concentration of characteristic plant types along watercourses is typical of many Savanna streams and may be the result of burning (Grove, 1973).

FIGURE S-4.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1111–09483, November 11, 1972) of the area near Tillabéry, Niger, showing arable alluvium along the Niger River, the principal dune deposits, and small dark areas (A) and drainage that may indicate sources of shallow ground-water supplies. (Approximate scale is 1:1,000,000.)

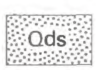
EXPLANATION S-4

Small dark areas showing on MSS bands 5, 6, or 7 indicate vegetation and possibly damp areas that may indicate shallow ground water. Images 1111–09483 (November 11, 1972) and 1271–09484 (May 10, 1973, which is not shown) were also used to compare conditions at the beginning and near the end of the 1972–73 dry season. Some of the damp areas, if present, may contain water too salty for human or livestock use because most potable shallow ground-water sources probably would already have been developed by the local inhabitants (John Buursink, oral commun., 1974). A cursory inspection from a commercial jetliner revealed that some of the dark areas appear to be depressions—lined or underlain by dark clayey deposits—which probably act as tanks holding water temporarily. A few of the dark areas contained ponds as of November 11, 1974, and are so noted on the figure.

Major drainageways that appear as dark strips on MSS bands 5, 6, or 7 of images 1111–09483 and 1271–09484. The dark strips indicate mainly riparian vegetation whose growth is dependent upon ephemeral streamflow and bank and channel storage. In some places, shallow ground-water supplies might be developed along these drainages.

Channel and flood-plain alluvium undifferentiated along the Niger River. If developed intensively, farm products grown on these deposits could help in alleviating food shortages that occur from time to time in Mali and Niger.

Braided channel of the Niger River.



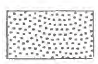
Area of extensive eolian deposits (including deposits forming sand stripes). Includes some alluvial deposits. Thickness not known.

Area of alluvium, laterite, and consolidated rocks generally not overlain by extensive eolian deposits. Includes the Continental Terminal valley fill deposits.

FIGURE S-5—Part of Landsat frame 1110-09424, MSS band 5, showing alluvial deposits of the Dallol Bosso and the Niger River near Niamey, Niger. (Approximate scale is 1:1,000,000.)

EXPLANATION S–5

Some of the most interesting features of the northern Savanna and southern Sahara, readily identified and mapped from the Landsat imagery, are the dallols, which represent ancient and now largely unused drainage systems developed during more humid climatic conditions of the Pleistocene Epoch. The dallols are well-known physiographic features; they are shown on the geologic map of Niger (Greigert and Pougnet, 1965) and on other maps. The Landsat data provide a convenient method for quickly obtaining information about the size, distribution, and, perhaps, the vegetation and soil cover of the dallols. Only Dallol Bosso, an ancient valley east of Niamey, was inspected during the present investigation (fig. 16). There the alluvium is extensively hand cultivated and grazed. The presence of dug wells indicates that considerable ground water occurs at a shallow depth along the floor of the dallol, although the amount of water in storage and its chemical quality is not known. Comprehensive investigations, including some test drilling, would determine the extent to which the dallols can be developed for agriculture.



Alluvial deposits of Dallol Bosso drainage system. The dallols of West Africa drained generally southward toward the Niger River or interior lowlands during Late Pleistocene time.

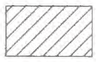
Channel and flood-plain alluvium undifferentiated along the Niger River.

Braided channel of the Niger River.

FIGURE S-6.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1079-10102, October 10, 1972) showing part of the Inland Delta of the Niger River near Tombouctou, Mali. The image provides a spectacular view of the below-normal 1972–73 flood of the Niger River, lakes and ponds fed by overflow distributaries of the river, broad lowlands or depressions of the Inland Delta that are subject to inundation by normal or above-normal floods, and extensive dune tracts composed of stabilized and active dunes. (Approximate scale is 1:1,000,000.)

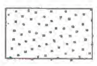
EXPLANATION S–6*A*

An effective application of the Landsat imagery is the mapping of floods. From this image, the 1972 annual flood of the Niger River can be readily mapped. Muddy flood waters (blue) are especially conspicuous on the false-color composite and can also be seen clearly on black-and-white images of MSS bands 5, 6, or 7.



Extent of the annual flood of the Niger River on October 10, 1972. The maximum width of the inundated area shown at the bottom of the image is 85 km.

Small distributary channels of the Niger River.



Main lowland areas of the Inland Delta subject to inundation when flood crest passes. Outside boundary is indicated by a long dash (——).

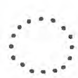
Approximate area mainly underlain by unconsolidated surficial deposits of dune sand and alluvium of the Inland Delta.

Approximate area mainly underlain by consolidated sedimentary rocks.

— — — — — — —

Highly generalized contact between sedimentary rocks and surficial deposits as mapped from the Landsat imagery.

Direction of strike of folded sedimentary rocks.



Area masked by clouds and shadows.

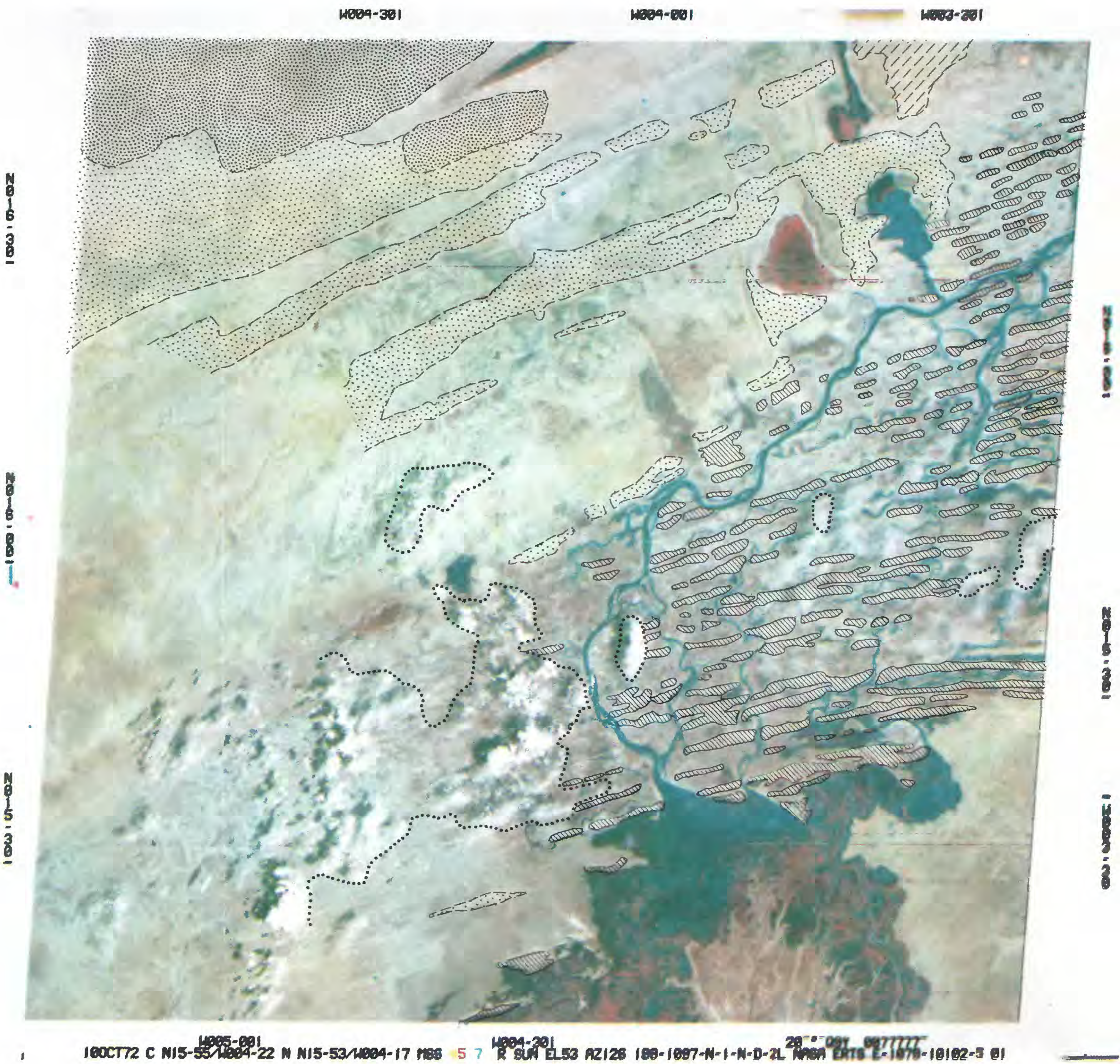
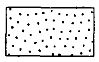


FIGURE S–6.—False-color composite Landsat image (MSS bands 4, 5, and 7 of 1079-10102, October 10, 1972) showing part of the Inland Delta of the Niger River near Tombouctou, Mali. The image provides a spectacular view of the below-normal 1972–73 flood of the Niger River, lakes and ponds fed by overflow distributaries of the river, broad lowlands or depressions of the Inland Delta that are subject to inundation by normal or above-normal floods, and extensive dune tracts composed of stabilized and active dunes—Continued. (Approximate scale is 1:1,000,000.)

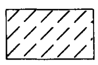
EXPLANATION S–6*B*

Dunes and areas of other eolian deposit types can be identified easily on Landsat images from either false-color composites or black-and-white images, preferably of MSS bands 5 or 7. Interpretation of imagery, accompanied by onsite checking, could probably furnish enough information to aid in studies of the southward encroachment of the Sahara and desertification in the Sahel.

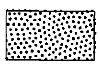
Stabilized longitudinal dunes trending east to east-northeast (solid-line contact). A reddish-brown soil is developed locally on these dunes.



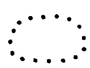
Main areas of sand sheets or sand stripes (dashed-line contact).



Modern longitudinal dunes trending approximately northeast (dashed-line contact).



Erg (shifting sand); lines of the dune crests trend approximately north-northwest (dashed-line contact).



Area masked by clouds and shadows.

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