HAPEX-II-SAHEL

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A WATER AND ENERGY BALANCE MODELLING PROJECT IN DRY TROPICAL CLIMATE

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INTRODUCTION AND CALL FOR AN INTERNATIONAL COLLABORATION

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SUMMARY

THE HAPEX-II-SAHEL PROJECT

INTRODUCTION

Interactions between land surfaces and the atmosphere govern to a large extent the water and energy exchanges that drive the climatic system. In the quest for a better understanding of the dynamics of the earth's climate and its fluctuations, the World Climate Research Programme (WCRP) has instigated surveys of surface-atmosphere exchanges under different climatic, hydrologic and pedologic conditions. These experiments, forming the HAPEX programme (Hydrological Atmospheric Pilot EXperiment), combine methods from various disciplines (meteorology, hydrology, bioclimatology, satellite imagery, etc.) to study the earth's water and energy balances. The study zones measure approximately 100 x 100 km, considered to be the smallest area capable of giving meaningful results from the climate modelling point of view.

The first HAPEX experiment (HAPEX-I, or HAPEX-MOBILHY), conducted in south-west France from 1985 to 1987, has made it possible to check the experimental design and has provided a comprehensive data base on the surface-atmosphere interactions at mid-latitudes in the Northern Hemisphere for various land use conditions (forest and agricultural). The initial results (ANDRE et al., 1988) are highly encouraging and have made it possible to propose and check new water and energy exchange parametrization schemes (NOILHAN and PLANTON, 1989).

The priority of the continued HAPEX is now to study surface-atmospheric interactions in semi-arid environments. Such conditions prevail over large areas of the earth's surface, many of which are menaced by desertification, inducing a dangerous global disequilibrium. The new experiment, referred to as HAPEX-II, is designed to mobilize all African, American and European groups immediately concerned by desert expansion. A coordinated effort has been planned, starting with a preliminary study and followed in all probability by two in-depth investigations :

- In 1991, as a preliminary phase, tests will be carried out on the adaptation of the equipment to dry conditions and a satellite programme will be developed for HAPEX-II, more complete than the one implemented for the HAPEX-MOBILHY experiment. This work will be conducted at the La Mancha site in Spain, in part to facilitate the testing of equipment developed in various European laboratories and also to prepare for a subsequent phase (1994, see below) focusing on erosion phenomena and the consequences in southern Europe.

- In 1992, the main experiment, HAPEX-II-SAHEL, will be carried out east of Niamey in Niger, where a basic infrastructure and the results of numerous specific investigations in hydrology, remote sensing using satellites, surface balances, climatology, etc. are already available.

The HAPEX-II-SAHEL experiment, outlined below, must now be carefully planned and implemented, requiring close international cooperation. It will provide the necessary data for a description of the exchanges between the earth's surface and the atmosphere over the extensive intertropical regions of the planet, and should lead to significant improvements in global climate modelling.

- In 1994, based on the experience acquired, an experiment referred to as Erosion and Desertification - Spain will be conducted on the La Mancha site with, as a main objective, the characterization of the climatic environment of southern Europe, also menaced by desert expansion. This operation, to be conducted two years after HAPEX-II-SAHEL, will investigate desertification under the less drastic European conditions using the methods developed for HAPEX-II-SAHEL.

The concentrated effort described above is covered by an agreement in principle reached between a large number of organizations of various origins :

- France. PNEDC (the National Climate Dynamics Investigation Programme), ORSTOM (French Institute of Scientific Research for Cooperative Development), the French Meteorological Office, INRA (the National Institute for Research in Agronomy), etc.

- Europe. European Community Commission (ECC), etc.

- North America. NASA.

- International. ISLSCP (International Satellite Land-Surface Climatology Programme), WCRP (World Climate Research Programme), UNEP (United Nations Environmental Programme), etc.

1. SCIENTIFIC BACKGROUND

1.1. GENERALITES

The evaporation flux, in particular is related both to the state of the atmosphere and to the avaibility of water at the surface. One can suspect, then, an interaction between surface hydrology and atmospherical circulations. This can be studied using climate models, and ROWNTREE and BOLTON (1983), YEH et al. (1984) have shown that soil moisture anomalies have an impact on atmospherical circulations and precipitation patterns. In some cases anomalies will last for several months. It is important, then, to describe correctly surface hydrology in climate models. In early simulations, simple parametrizations schemes such as BUDYKO's "bucket" method were used. These simple methods, however crude, provide the necessary interactions but fail to differentiate surface types and vegetations. Besides some systematic errors are inherent to the method. Acknowledging the importance of surface hydrology, modellers have since then improved the representation of these processes, trying in particular to take vegetation into account (DICKINSON, 1984, SELLERS et al., 1986).

Although studies by, for instance, LAVAL et al. (1984) have shown that climate models are sensitive to the formulation of evapotranspiration at land surfaces, it is difficult to select directly a parametrization from model results.

1.2. RATIONALE FOR PILOT EXPERIMENTS

One way to improve the description of surface hydrology into climate models is to promote specific experiments. Most of the existing data are small scale and for this reason, not fully by relevent for climate studies, where variables are computed over grid squares larger than 10 000 km^2.

Observing land surface hydrology and evaporation over most natural surfaces at this large scale is a difficult task which shows a great variability. The outstanding difficulty results from the fact that soil parameters vary over short distances (i.e. 100 m), but quite slowly in time (i.e., 10 days) while the atmospheric boundary layer varies more smoothly in space (on a 10 km scale), but much faster (i.e. 1 hour). Matching these antagonistic characteristics was the purpose of the first HAPEX experiment (ANDRE et al., 1986) executed in 1986, in the temperate climate of south western France in an area of smooth topography. The experimental strategy was based on existing networks of raingages and automatic weather stations supplemented by measurements of energy and water budgets at selected locations. Integrative methods such as basin hydrology, direct flux measurements from aircraft, and atmospheric budget method were also used. As part of the programme, a strategy for the use of the data set was also worked out, based on the use of atmospheric mesoscale modelling and implemented for selected days (ANDRE and BOUGEAULT, 1988). This particular experiment, together with other observational studies such as FIFE in the United States, provides ideas about the observational techniques that can be combined to monitor land surface processes. Using such methods, one can then proceed to study areas of particular significance for the global climate.

1.3. AN EXPERIMENT IN DRY TROPICAL AREA

1.3.1. General features

The case of temperate Europe is in some respects a fairly "easy" one case. Evaporation is close to potential during a great part of the year. Annual cycles of soil moisture are quite regular and similar from year to year. Except for dry spells most parametrization schemes of evapotranspiration give somewhat similar results.

The situation is very different in dry tropical countries, such as Niger, where rainfall are much more concentrated in time and much more irregular. Runoff is important and the regional water balance difficult to assess. Most of the time, potential, evaporation is much larger than precipitation, and large errors are possible when discomputed evaporation in a drying sequence. On the other hand, because of the lack of topography and because of the steadiness of the pressure patterns in these areas, the atmospheric forcing (except for squall line events) seem to be simpler than in the european case. It is thus likely, that the boundary layer of the atmosphere can be a good natural integrater for the water fluxes emitted from the surface as a result of complex phenomenas.

The "Working Group on Land Surface Processes and Climate" (WMO, 1985, 1988a and 1988b) recommends conducting such experiments in other climatic conditions.

The sahelian dry tropical climate offers the largest climatic contrast between dry and wet seasons (in contrast to the relative interannual regularity in temperate rainfall), because most of the rainfall (almost 80 % of the annual total) falls from July to September (with a monthly maximum in August), and because the median is close to zero from November to March (figure n°1). On the other hand, soil and vegetation are relatively homogenous in Sahel, in contrast with temperate regions.

Moreover, the variability of sahelian surface runoff capacities leads to a larger heterogeneity in surface water resources compared with temperate areas.

Finally, desertification, due to a significant rainfall shortage, has arisen in the Sahel over the last 20 years (SIRCOULON, 1986), resulting in the gradual exhaustion of vegetation and altering energy and water exchange between the continent and the atmosphere. It is therefore very important to establish the vegetation's hydrological and energetic characteristics in order to simulate the effects of drought using climate models.

1.3.2. Specific goals

The following points are of particular interest :

- Monitoring the water balance during the rainy season and during the drying phase in a semi-arid region taking into account the development of the natural vegetation (savannah) and of the cultived areas.

- Study of situations of large imbalance between atmospheric demand (potentiel evaporation) and real evaporation and of situations of severe stress. Modelling of such cases and computation of relevent regional surface resistance.

- Assessment of the importance for regional fluxes of the spatial variability due to rainfall and runoff patterns, as opposed to the variability due to vegetation type.

- Because of the relative simplicity of surface characteristics in the area, remote sensing both from aircraft and from satellite should be used extensively and this calls for specific studies, such as the use of surface temperature to estimate sensible heat fluxes.

2 - THE SAHEL

2.1. FACTORS INVOLVED IN SELECTING THE STUDY AREA

2.1.1. Location

The square area suggested for such an experiment lies between longitudes 2° and 3° East and latitudes 13° and 14° North (figure n°2) and has smooth relief (maximal variation of 100 m over 10 000 km^2).

Niamey, capital of Niger, is located at its western edge.

This zone is typical of the large sahelian areas situated between isohyets of 400 and 800 mm, from N'Djamena to Kayes (figure n°3).

Below we describe its main characteristics based on studies already conducted in the area.

2.1.2. Main characteristics

2.1.2.1. Pedology

Numerous pedological studies have been carried out of this area, especially by GAVAUD (1964), who compiled the soil map of the Western Niger, and by COLLINET (1988).

As described in figure n°4 , the area of tropical, ferruginous soils spreads from North to South, from the 400 mm to 1 300 mm of rainfall isohyets, from the North-West of the Ivory Coast ; and from East to West, from Lake Tchad to Dakar through Kano, Niamey, Ouagadougou and Bamako.

Several authors subdivide the area into two subsets : the first mainly comprises a leached ferruginous soils, and the second crystalline soils and their alterites (leached, ferruginous soils). This subdivision hides the uniformity of tropical, ferruginous soil pedogenesis.

Among these soils, different types are associated with their location along the toposequence, thus :

- lithosols, often fine gravelled, occur at the top of the slope,
- soils comprising ancient kaolinic debasing materials, in the middle,
- and finally, at the base vertisols, halomorphic and hydromorphic soils.

Ferruginous soils often present a dune shaped relief with a strong slope. They can rapidly soak up initial rainfall, but they can then become choked and the runoff increases.

2.1.2.2. Geology (GREIGERT, 1966 ; GREIGERT and POUGNET, 1965)

The Continental Terminal extends on the left bank of the Niger, from Gao to Nigeria.

The classical aspect of Continental Terminal includes sandstone under the ferruginous crust, sandy alluviums, and grey and white clays upon a crystalline base.

The very large Continental Terminal groundwater table is located on cretaceous and eocene formations. It is an unlimited and continuous groundwater table because there is no superimposed impervious level.

It extends on the left bank of the Niger from the river to a line which runs from Tahoua to Menaka.

The water supply to this groundwater table comes mainly from local surface runoff.

2.1.2.3. Vegetal cover

a) Natural vegetation (AMBOUTA, 1984 ; GROUZIS, 1988).

Zonal variations in vegetation covers occur from South to North, and influence size, species content and the tree density.

There are two main types in the sahelian area :

- scrubby steppe occurs where the interannual rainfall is below 500 mm, and has few ligneous species.

- tree savannas occurs where rainfall is between 500 to 800 mm, and are more common in the Western Niger.

There are two qualifications in this zonal structure :

- on the Continental Terminal sandy plateau formations the vegetation is represented by bushes, no higher than three meters, separated by areas of bare soil ("tiger bush" type vegetation). This "tiger bush" covers about 50 % of the area.

- "dried valley" formations ; (Dallol Maori, Dallol Bosso...) which are filled by sandy alluviums, are intensively cultivated. The natural vegetation is represented in isolated spots and fallows.

b) Cultivations

90 % of the cultivated land is dedicated to millet (*Penissetum* spp.), mostly located on sandy formations. For few years out of season crops, such as "niébé" (*Vigna unguiculata*), have been cultivated during the dry season temporary waterholes.

Agricultural work is carried out by hand and is extensive : brief preparation is by tree-clearing followed by seeding (without land surface preparation), and uses natural manure from cattle.

The main field activities are seeding (as soon as the soil is wet, 30 to 40 cm deep), weeding, and harvesting during September and October.

2.1.2.4. Climatology

The main climatic characteristics obtained at the Niamey airport synoptic station are typical of the sahelian regime. They are given in the attached table.

We add the following informations :

The main wind direction is from the North-East during the dry season, and from the South-West during the wet season with short duration strong winds from East-North East when squall line fronts cross in the wet season.

These squall lines produce rainfall of short duration, sometimes with high intensity when the shower starts, followed by rain with more moderate intensity.

Correlations between rainfall intensities and duration have been established for the Niamey airport station (BOUVIER, 1986).

The existing daily rainfall data have been put into computer compatible form by ORSTOM. The period runs from the initial recording up to 1980. A first edition concerns data recorded up to 1965 : a second edition is curruntly being printed for the period 1966 to 1980.

Sahelian data homogeneization is presently studied by ORSTOM, with a view to constituting operational data banks of annual and monthly rainfalls.

A recent paper (SIRCOULON, 1986) points out ORSTOM's contribution to rainfall knowledge in Africa. Since 1981, the National Meteorological Service of Niger has published, a periodic meteorological bulletin in which is classified the daily rainfall measured at all the stations.

The National network is made of :

- 14 synoptic stations, where climatical data are recorded every three hours,
- 7 agrometeorological stations, dealing with crop observations,
- 23 climatological stations, where temperature, hygrometry, evapotranspiration and rainfall are measured 3 times a day,
- 200 rainfall stations (including the stations mentioned above) where the rainfall is recorded at least once a day (figure n°5).

Two radiosondages are carried out daily at Niamey airport station at 12 h and 0 h TU. A radiosondages data bank for the period 1948 to 1965 is already constituted. Its extension to the 1966 to 1987 period is being carried out by the LMD.

In addition, the Forecast Center is equipped with a meteorological radar of 5 cm wave-length. The captor functions well (a film of the echoes obtained on this radar screen has been satisfactorily carried out during the squall line crossing of the 1988 wet season), but the digitalization chain is out of use. A new chain, financed by the French Government at the request of the Republic of Niger, will be operational in Niamey for the 1989 rainy season.

2.1.2.5. - Hydrology

A paper (LEFEVRE, 1961) summarizes the data recorded before 1961, in particular the Niger river hydrometry. From 1961, ORSTOM was in charge of managing the National Hydrometric Network until 1974 for the Western network, and until 1981 for the Eastern network. The networks were than managed by the "Service du Génie Rural", and then by the "Direction des Ressources en Eaux", with ORSTOM collaboration.

Since 1961 a hydrological directory, published yearly, describes the topographic and hydrological characteristics of stations in the hydrometric network. Three hydrometric stations are located on the Niger River in the project area (figure n° 6).

The second volume of the "Hydrological Monography of the Niger River" (BRUNET-MORET et al., 1986), summarizes all the data obtained in the interior delta and the middle Niger (from the interior delta exit to the Federal Republic of Nigeria border), from the beginning of studies to 1980.
A book (DUBREUIL et al., 1972) collects the data obtained by ORSTOM on experimental and representative catchments in Western Africa.

Catchment area studies undertaken in Niger since the publication of this book are quoted in the bibliographic list (CHAPERON, 1970 ; HOEPFFNER et al., 1983 ; CHEVALLIER et al., 1985 ; RIBSTEIN and LEBEL, 1988).

The sites of the studied catchments are shown in figure n° 7.

The data collected on network stations and representative catchments have permitted the evaluation of the Sahelian surface runoff, using charts (RODIER, 1975), and mathematical models (GIRARD, 1975). Finally, it has been established (CASENAVE and VALENTIN, 1988), that in the Sahelian regions, the percentage vegetal cover and surface reorganization are the main factors influencing infiltration. Under the Sahelian regime underground pedological structures are not related to runoff.

On the base of the few elementary soil crusting units, it is possible to study the superficial hydrodynamic characteristics using a rainfall simulator. It will then be a scientific challenge to operate a transfer from the plot to the mesoscale.

A document by DUBREUIL, written at the request of the World Bank in 1986, summarizes the positions and the perspectives of the French hydrological research in intertropical areas.

2.1.3. General Infrastructures

We have already mentioned the exceptional facilities available at the Niamey station (radiosoundings data and meteorological radar) which no other station currently has in the African Sahel, and the meteorological and hydrological networks in Niger, managed by the Direction de la Météorologie Nationale and the Direction des Ressources en Eaux, who have already proved their competence in the management of these networks.

It is important to underline that at Niamey there are a significant number of institutions seeking to develop and promote atmospheric and hydrological research. These are the Centre Régional de Formation et d'Application en Agrométéorologie et en Hydrologie Opérationnelle AGRHYMET (Regional Center for Training and Application in Agrometeorology and in Operational Hydrology) (CILSS - OMM - FAO - PNUD), the Laboratory of Atmospheric Physics and the Institute of Radioisotopes of the University of Niamey, ICRISAT, INRAN, and delegations from ORSTOM and BRGM in Niger.

2.1.4. Current and Outgoing Studies

2.1.4.1. Rainfall studies

The Meteorological Service of Niger, the LMD and ORSTOM are today undertaking a study of the spatiotemporal distribution of precipitations based on a network of recording raingauges with static memories (40 in 1988, 60 in 1989 and 1990) over an area of 10 000 km^2 to the East of Niamey (between 2 and 3° E, 13 and 14° N) for the ground validation from METEOSAT data and from the radar data (EPSAT programme) (figure n ° 8).
The proposed experimental material, which will be installed for the rainy season, are shown in figure 8.

2.1.4.2. Evapotranspiration

In 1988, INRA and IRAT carried out a campaign to measure the water balance using micrometeorological techniques, with measurements of the evapotranspiration during the rainy season from June to December 1988 on a plot of millet and on fallow land to the North of Niamey, using the simplified aerodynamic method, and on natural vegetation of the "tiger bush" type using the fluctuations method. Soil moisture neutronic measurements were also been carried out on each site.

Complementary measurements are planned for 1989, in association with the Institute of Geography of Copenhagen. ORSTOM is in the process of collecting a complete set of data on the cultivation of out-of-season millet near Niamey.

Since summer 1988, the Institute of Hydrology of Wallingford, with the support of ICRISAT, has been carrying out measurements of radiant energy and of fluxes of sensible and latent heat over three types of vegetation (natural savannah, savannah which has been denuded by desertification and cultivated millet) at Sadoré, to the South-East of Niamey (WALLACE et al., 1988).

2.1.4.3. Boundary layer , aerosols and radiation

The study of aerosol radiation on surface temperatures and their consequences on remote sensing measurements will be performed in the Niamey region by the laboratories of Atmospheric Physics of Abidjan and LMD (LEGRAND et al., 1988 a).

2.1.4.4. Remote sensing

The results obtained from the EPSAT network (CARN et al., 1989 ; GUILLOT, 1988) can, by combining the cloud statistics and surface temperature, provide good data on monthly (r = 0.92 in August and September 1986) and seasonal scale (r = 0.97 in 1986 and 0.96 in 1987) with an error less than 10% for season rainfall.

The research carried out by LERTS in the Sahelian region fits into the framework of the previous and present thematic activities : the observations of the water status of vegetation and its biological activities (KERR, 1986 ; SEGUIN et al., 1989).

- Agricultural water budget monitoring

Field data collected in Senegal from 1984 to 1987 have made it possible to calculate the heat fluxes in the air and in the ground, atmospheric corrections (radiosondage data) and net global radiation. The data used were essentially from METEOSAT thermal IR and AVHRR vegetation index measurements. On the basis of this data, algorithms were developed and checked for the plotting of isohyetal maps from surface temperature and evaporation maps. In addition, a method has been developed to provide rough estimates of millet yields (ASSAD et al., 1986 a b; LAGOUARDE and KERR, 1986 ; ASSAD 1987 ; KERR et al., 1987 ; BRUNET et al., 1989 ; IMBERNON and KERR, 1989 ; KERR et al., 1989 ; LAGOUARDE, 1989 ; LAGOUARDE and CHOISNEL, 1989 ;ASSAD, 1987 ; LAGOUARDE and KERR, 1986 ; KERR et al., 1987).

A model for the estimation of surface humidity and vegetation characteristics in the hyperfrequency domain has been successfully applied to a region in Senegal, with a 3-years data set (1983-1985) from the SMMR radiometer of the NIMBUS-7 satellite (KERR and NJOKU, 1988, 1989).

Algorithms have been developed and a data bank has been set up on the basis of 1983 to 1988 information from METEOSAT VIS and thermal IR channels in the form of monthly albedo, net radiation and surface temperature files (DEDIEU et al. 1987 a b). Furthermore, rainfall measurements obtained from METEOSAT B2 images have been extended to the entire Sahelian region and have shown very encouraging correlations (correlation coefficients of around 0.92 calculated over 120 stations for a seasonal estimate).

- Investigation of biorythms of Sudanese Sahelian vegetation :

This experiment began in May 1985 within the framework of investigations supported by NASA as part of its THEMATIC MAPPER EARTH SCIENCES programme and was scheduled to last three years. The objectives include the remote sensing characterization of the seasonal evolution of savannah environments and the identification of phenological parameters. The experiment was conducted jointly with the Institut de la Carte Internationale de la Végétation, the Institut de Recherche en Agronomie Tropicale, the Laboratoire d'Ecologie (Orsay - France) and local research organizations including the Tropical Ecology

Institute (Abidjan - Ivory Coast) and the Tropical Research Institute of Ecology and Botany.

As part of this experiment, two measurement campaigns were conducted during the dry season with a classical meteorological survey and measurements of optical thickness, field radiometry, rainfall, biomass and phenological characteristics of the vegetation and soil characteristics. These field programmes were carried out between October 1985 and May 1986 in Comoé National Park (northern Ivory Coast) and between October 1985 and June 1987 along a transect extending from Comoé Park to the Burkina Faso-Mali border (this transect is characterized by a pluviometric gradient of 650 mm over 750 km).

In parallel with this, THEMATIC MAPPER scenes in the VIS and near and mid IR bands were used to monitor the evolution of the phenological stage of the vegetation.

Independent of the TM investigation, which is drawing to a close, and as part of the preparations for SPOT 4, a continuation of the operation on the Bidi pilot site is planned by ORSTOM in the north of Burkina Faso in relation to an interannual monitoring of vegetation. The subsequent extension of the infrastructure to the Ouarkaye site (southern Burkina Faso) is also planned, which would broaden the savannah experiment to an agricultural region (traditional and industrial crops). This extension phase is schedule for 1990.

Elsewhere, the LSIT/GSTS (Strasbourg) conducted field emissivity measurements in 1988 north-east of Tahoua (central Niger), as part of the TAMSAT programme.

2.2. EXPERIMENTAL APPARATUS FOR AN HAPEX TYPE EXPERIMENT

2.2.1. Flux

As the objective is to integrate the flux over a square degree, it is convenient at first to characterize the flux field. This means carrying out representative measurements for the main "vegetation soil/type" associations, taking into account the distribution of hydrological parameters (rainfalls, surface runoff...).

The aim is to set up a data collection network. Only the simplified aerodynamic method is workable as single network of 10 to 20 stations (because of power and maintainance problems). We could envisage also using the Bowen ratio method, only if it is proved that this type of measurement is feasible with a non-mobile apparatus, such as the BEARN system (already tested by several research teams). Such a network can only be installed over low vegetation (height under 2 m).

Particular care will be necessary in order to ensure correct measurement of the ground heat flux which, in contrast with temperate latitudes where the soil is covered with vegetation, is a large term in the energy balance. It would be appropriate to take into account the results of the ECLATS project on this subject (DRUILHET et al., 1988).

Amongs the other conditions to be considered, it is necessary to stress :

- the use of recently calibrated sensors (in particular radiation sensors) ;
- the frequent recording of vegetation heights during the growing season (and then to adjust the position of the stations) ;
- the rapid availability and a real time monitoring of the collected data ;
- the measurements of classical meteorological parameters such as wind direction, hygrometry, temperature and rainfall.

Finally, the ECLATS experiment has indicated a deficit of sensible heat flux during the afternoon : in free convection conditions, a radiative transfer mode may intervene in the turbulent transfer. The absorption of solar radiation seems to be very important when "brumes sèches" occur. It will be necessary to characterize this phenomenon and to take it into account, particularly for the monitoring of thermo-dynamic profile evolution, as measured by radiosounding, after having clearly demonstrated that this phenomenon is not the result of an instrumental mistake, but truly related to a divergence in the Infrared flux.

The interest in more detailed additional, measurements (masts,...) is obvious, but can only be considered at a limited number of sites, i.e. :

- at a central site, used as a reference,
- in areas where the vegetation size is too high to allow other measurement techniques.

Because of the vegetal distribution as two main types (savanna and cropped land), because of the soil homogeneity, and bearing in mind the lack of relief, we propose the following :

- at least twelve stations over cropped areas or grassland which make flux measurements and record classical meteorological data (4 M stations of the CNRM).
- some instrumented masts on "tiger bush" (INRA, INSTITUTE OF HYDROLOGY...) associated with a neighbouring measurement station located between tree lines, to measure the difference between tree evaporation and bare soils.

2.2.2. Rain

The ground network of the EPSAT programme, which was described in section 2.1.4.1. will serve as the main tool for measuring precipitation over the square degree area. Coupled with a 5 cm weather radar system, this network will provide good estimations of precipitation entering in the elementary units for further modelling.

2.2.3. Soil moisture

The soil moisture, which is a function of the fraction of infiltrated water, will be measured at the same sites as the energy balance using neutron probes with additional data from weight measurements.

Soil moisture evolution will be followed by porous ceramic tensiometers. The drying of the reservoir will be measured using micropsychrometers.

2.2.4. Surface runoff

Surface runoff capacities of the square degree surfaces will be evaluated from a large inventory of existing soil crusting.

Discharge measurements will be performed at the outlet of ten catchments, located on the square degree with areas varying from 1 to 1000 km^2 and with contrasted soil crusting associations (figure n ° 6). So, it will be possible to determine scale effects in the transposition of point measurements to larger areas, taking into account the hydrological degradation phenomenon representative of hydrological regimes in the Sahel.

It should then be possible to estimate the recharge available to free groundwater table, and, by difference, that available to the atmosphere.

2.2.5. Vegetation

The vegetation of the study area is divided by two main factors the geomorphology and human activities.

The "tiger bush" formations occupy sandstone plateaus of the continental terminal, they present facies more or less degraded depending upon anthropogenic activities.

The savannah shrubs or tree formations on sandy substrates have almost completely disapeared because of extensive cultivation. They are found only in reduced numbers or in very old fallows.

Even the dry valleys (Dallol) are intensively cultivated.

In the anthropogenic formation, composed of fallows and cultivated fields, we distingish different facies based upon the density and ligneuse substrate maintained in place. In a manner that the zone supports largely diversified vegetation.

Considering the HAPEX objectives : characterization at different scales, the fluctuation of water and energy in interaction with the surface formation - atmosphere, the role of the vegetation consists of :

- redistribution of incident rain water. Vegetation by its structure influences the soil surface features and drainage which contribute to a heterogeneity distribution of surface water.

- influence the energy transfer and evaporation of surface water. The ground cover, by its physiologic state and functioning, regulates a part of the water transfer from soil to atmosphere over space and time.

The studies to perform :

1 - The classification and mapping of the terrain and its heterogeneity.

2 - The definition of functional units (plant structure, soil, hydrological regime).

3 - The characteristics of the interaction of the terrain and the importance of the redistribution of the fluctuation.

4 - Follow the phenology of the vegetation, both the seasonal dynamics with the annual rains and the ligneuse substrate and herbaceous on a functional level.

These studies depend upon the utilisation of high resolution satellite data (SPOT, LANDSAT TM) and data obtained from studying terrain characteristics, vegetation structure and soil surface features conditions. These require an interface on the local level with surface water hydrology and soil hydrological balance in order to integrate them into the simulation model. The determination of some vegetation ecophysiological parameters may also be necessary.

2.2.6. Radiosondages and sodars

Given the relative simplicity of the advection of the experimental area one can hope to estimate advection from wind speed soundings.

In more complicated situations, a small grid analysis model would be necessary in order to define the advection field using radiosondages data and ST radars data.

Moreover, WEILL (1988) has clearly shown the potential of sodar to estimate changes in virtual temperature and the movement at the square kilometer scale. The use of data from radiosondes and from sodars are therefore useful to derive an algorithm for the transfer from point data and integrated measurements representative of larger scales derived from airborne and satellite data.

The use of sodar in the HAPEX-II-SAHEL will essentially center on the scientific theme of spatial extension of flux measurements. This area of research requires obtaining data from a varity of instruments in different surface and climatical conditions. In particular we can analyse the "lack of flux" at noon in the sahelien zones, which could be the result of radiation or a large convective structure.

An interesting experimental configuration is to locate two sites which effect the flux differently (relief, vegetation etc...). In essences this will permit the development of the second scientific theme : the relation between the boundary layer and the heterogeneity of surface condition.

The sodars should be situated near instruments, permitting the measurement of wind speed and temperature fluctuations in an effort to utilise and compare complementary observation data. Only a few instruments are listed below :

An instrument such as a ST radar which measures wind speed at a higher altitude than the sodar (15 m - 400 m for the sodar, 400 m - 700 m for the UHF radar), is complementary to the sodar. It would be used to characterize geostrophic circulation (with and without advection), in the inversion zone regardless of its altitude.

Measuring air fluctuations on the ground is necessary for an integral study of flux. On this point the data obtained from the HAPEX-I-MOBILHY, which is currently being analyzed, illustrates this difficulty and reveals that each instrument must be calibrated before comparing results.

Temperature profiles (radiosondage) are very important for our studies. They permit us to characterize the thermal stability of the atmosphere.

2.2.7. Data bank

A first step toward a rational organization and improved data analysis is for all the participants to adopt a data exchange format. This format should be as universal as possible. The simplest would use the current standards and collective habits the ease the transportation both in space (different sites) and in time. In addition the data collected today might be useful later as new concepts develop. Thus the data should be safely archived.

The organization of the measurements cannot be performed without perfect knowledge of the scientific themes of each participant who must define the data required for their study (observation or results of numeric modeling) with a resolution both spatial and temporal. The first step, if possible, is to develop within a workgroup, the data exchange format for the HAPEX-II-SAHEL.

2.3. MODELLING

2.3.1. Atmospheric Modelling

Atmospheric modelling has proved to be a major contribution in HAPEX-I-MOBILHY (ANDRE and BOUGEAULT, 1988).

At small scales, 1D transfer models of the continuum soil-plant-atmosphere, once calibrated with real data, can satisfactorily simulate water and heat transports over locally homogeneous vegetal covers. Schematically, the generation of such data bases is a two steps process : the experimental phase preceded by a preliminary phase of exhaustive documentation upon the climatological and hydrological characteristics of the domain. Soil (nature, texture, structure, depth,...) and plant (height, spacing, stomatal resistances,...) properties as related to heat and water transports, their spatial distribution and variability must be also studied.

At the mesoscale, when a minimum of measurements and synoptic analyses are avalaible, modelling can provide an accurate and detailed description of the atmospheric forcing for HAPEX-II-SAHEL, two further synoptic radiosoundings should be made available (e.g. at Zinder and Ouagadougou) for the enhancement of the European Center forecasts and analysis. Furthermore, more frequent soundings at Niamey are required in order to improve our knowledge of the atmospheric phenomena over the domain at increased temporal resolutions.

Thus initialized, a 3D mesoscale model could prove to be a valuable tool for the spatial integration of point measurements, with a spatial model resolution (typically 10 km x 10 km) compatible with the aircraft flux measurements and the satellite data.

2.3.2. Hydrological modelling

The efforts to model hydrological conditions in the large sahelien basins are few but they allow the isolation of certain difficulties and their particular functioning. When modelling the Oued Ghorfa in Mauritanie, GIRARD (1975) underlined that satisfactory runoff modelling in the Sahel is not possible without sufficient precipitation data and information on the physical environment. The first step is thus the acquisition of this knowledge, calculation of precipitation estimation errors on elementary surface areas, classification of surface states, mapping of the hydrological network and drainage zones.

The second step is to study the interaction between spatial variations of precipitation and surface states in order to determine the pertinent scale at which the spatial variability must be taken into account and the associated temporal resolution. The water table fluctuations will then be quantified and their interaction with the drainage surface, will be modeled.

At least two modelization schemes will be compared : a simple model with few parameters and a distributed model based upon the studies described above.

Acquisition of SPOT images and a Digital Elevation Model are indispensable for this work.

2.3.3. Hydrogeological Modelling

Hydrogeological modelling permits the study of underground water transfer and the loss of ground water via evaporation.

The modeling of underground drainage is impeded in part by the estimation of local rainwater infiltration and by poor knowledge of surface hydraulic grade line of the water table and depth for several dates.

On the other hand observation of dried river beds and the ancient and current temporal evolution of the hydraulic grade line in wells should provide elements satisfactory for hydrogeological modeling.

In addition to the exact knowledge of surface water contribution, from the north by koris Ouallam and Dantiandou and on the north-east border by Dallol Bosso the estimation of underground water, positive from the north and negative to the south, has to be carried out.

On a daily scale, the data received (rain, runoff, infiltration, evaporation and evapotranspiration) should be sufficient to assure the modelling of subterranean transfer throughout the hydrographic network. The calibration of the model presents a more difficult problem than that encountered in the HAPEX-I-MOBILHY study of south-western France, but can be considered as solvable.

The interest in this model is important enough to require complementary measurements. Also it is necessary to :

- select and level, with precision, 15 water points within the zone.
- install 10 recording piezometers with static memory
- perform an exhaustive search for hydrogeological data already obtained in the region before using the model on the period 1970-1992.

2.4. REMOTE SENSING

It is planned to use remote sensing to provide spatial representation of the surface energy state (surface temperature and albedo) and of the production of vegetation cover.

In order to estimate actual evapotranspiration, it is proposed to monitor surface temperature using infrared thermography, with the METEOSAT and NOAA satellites.

Biomass evaluation will be made from NOAA-AVHRR data by the combining channels to determine the vegetation index and by modeling the radiative transfer for different covers taking into account the growth characteristics and order external parameters.

Integration and extension of local measurements by remote sensing is paramount to this experiment, since the aim is to reconstitute the fluxes to the mesh scale of the general circulation models on the whole of the Sudan-Sahel area. As concerns the fluxes, satellite radiative measurements accurately validated by ground measurements are the most direct way to obtain radiative fluxes : rising radiative fluxes, linked in the short-wave range to albedo and in the infrared to surface temperature (and its emissivity) ; descending radiative fluxes, linked mainly to characteristics of the atmosphere and to the presence of clouds or atmospheric dust.

The description of the nebulosity parameters and of the atmospheric aerosols is thus fundamental to these satellite measurements of radiative fluxes, and fundamental also to the measurement of evapotranspiration according to ground temperature (clouds and dust modify ground temperature and even more so the apparent temperature as calculated by satellite). It has thus been planned to observe these cloud parameters, by means, on the one hand, of AHVRR and NOAA and, on the other, of METEOSAT, so as to take more precisely into account the short-scale temporal fluctuation, and especially the day-time variations. Physico-statistical correlations will then be searched between these cloud parameters and the fluxes as measured on the ground.

As regards rainfall remote sensing will not be of great use at the level of the large zone (between 2° and 3° E, and 3° and 4° N), this is taken care adequately by the pluviographs network and a meteorological radar, but the spatial extension of the measurements to a vaster domain through IR and/or microwaves satellite measurements will be possible thanks to the local validations.

The meteorological satellites will also help define the synoptic environment of the experiment, especially badly described by an inadequate ground network. For example, confronted with the appropriate cloud tracers, wind fields can be restored to some atmospheric levels. This will be made easier by satellite broadcast, every half hour, of the MOP series of visible images with a 2,5 km resolution.

NOAA/AVHRR data permit, among other things, the temporal evaluation of the plant cover, the mapping of large zones, in order to follow the principle phenological phases and surface temperature during data acquisition and eventually the evapotranspiration.

MOS-1 data will be used to determine the content of atmospheric vapor and their main locations and follow the evolution of vegetation as it becomes sparser.

SPOT and TM data will be used to map the terrain, plant cover and soil surface conditions. METEOSAT data will not only permit the following of daily cycles of surface temperatures but also determine the albedo of the surface and global solar radiation.

The SMM/I sensor of the DMSP with its micro-wave data channel will be used to define precipitation zones.

Finally, the use of the following radiometers with air transport for experimentation :

Ultra-high frequency radiometer of PORTOS, available on ARAT (Fokker 700) of the INSU in 1991 will permit the estimation of soil humidity at different depths and certain aspects of the vegetation (integral humidity) and the soil (roughness). Equaly desirable is the ultra-high frequency radiometer PBMR of NASA, with its complementary frequency to PORTOS of 1.4 GHz.

The infrared radiometer TIMS supplies surface temperature on a median size scale as well as information about some spectral emissions. It is desirable to have access to a more classic large band radiometer such as IRT.

The radiometer visible/near infrared - red/median infrared.

The evaluation of surface radiation fluctuation is proposed using METEOSAT's visible and infrared data. An algorithm for calculating the short wave fluctuation (DEDIEU et al., 1987 a b ; LEBORGNE and MARSOUIN, 1988) was tested in France. A precision of 10% was obtained for daily values. The study is now at the stage for testing with longer waves. An algorithm should be ready in time. The sensors to validate the algorithm for short wave radiation flucturation will be installed in the sahelien zone.

Finally the IGBP is very important for analysis of the hydrological balance and plant composition. The HAPEX-II-SAHEL will add greatly to this comprehension. The use of satellite data, particularly the surface temperature and to test the algorithms on a large scale will supplement our knowledge considerably.

2.5 AIRBORNE MEASUREMENTS CONTRIBUTION

The use of two aircrafts equipped for turbulence measurements, should allow an adequate sampling of the flux field (simultaneous information along different axis). The ARAT (Fokker 700) aircraft of INSU and the FAIRCHILD MERLIN IV aircraft of CNRM should fulfill these objectives. In addition to measuring small scale dynamics measurements in the ABL, the lidar aboard ARAT, should provide further information about its internal structure.

- Spatial integration of surface fluxes.

Flights performed at low level (50 to 100 m) provide turbulent surface fluxes of sensible heat, latent heat and momentum. Previous remarks about the contribution of the different scales which contribute to atmospheric exchange, imply a flight grid (over 100 X 100 km, for instance) involving horizontal longitudinal and transversal axes to define correctly the characteristic scales of the ABL. The simultaneous use of both aircraft should allow this over daylight periods when the fluxes remain almost constant.

Airborne measurements should therefore allow the spatial integration of surface fluxes and local characteristics (roughness, surface temperature). Such estimation has been made during experiments such as TOSCANE-T over the ocean, and MESOGERS over complex terrain, and demonstrated significant variability in fluxes over 50 x 50 km areas.

In short, airborne measurements provide :

- validation of the spatial representativity of local surface fluxes measurements,
- spatially averaged fluxes to validate/calibrate flux estimates obtained at larger scale by airborne or satellite remote sensing.

- Fundamental study of the ABL.

The dynamics measurements performed with the aid of both aircraft should allow to describe :

- the turbulence scales : typically of the order of the meter to the kilometer,

- the internal structures of the ABL : from one to ten kilometers,
- the mesoscale three-dimensional flow at the scale of 100 x 100 km through the computation of horizontal divergence, vertical vorticity, and mean advection of heat and humidity.

To meet this objective it is necessary to fly in several horizontal planes similar to those used for surface measurements from 50 m to the top of the ABL. Access to the top of the ABL, characterized by a temperature inversion, is however difficult with this measurement programme. Providing aerosols are numerous, lidar data could provide usefull additional information.

These measurements should study temperature and water balances in the ABL by defining the relative contribution of the different terms (turbulence, advection, heating and hygrometry rates).

3 - NATIONAL AND INTERNATIONAL CONTEXT

The National Programme of Study of the Dynamics of the Climate (Programme National d'Etude de la Dynamique du Climat (PNEDC) has favorably received the idea of an evaluation of the water balance in a dry tropical region to test and improve the parametrisation of climate models of the GCM type, so as to characterize the evaporation and the humidity of the soil. PNEDC has given this project highest priority in its atmosphere subprogramme.
The PNEDC organised a symposium on November 7-9, 1988 at Villefranche sur Mer during which the HAPEX-II-SAHEL project was presented.

On the international level, the World Climate Research Programme (WCRP) recommends, through its Working Group on Surface Processes and Climate, to move to homogeneous zones which present contrasting conditions in their water balance, with a short, single rainy season. The African Sahel fits this criterion, with a single rainy season in July, in August (monthly maxima) and in september.

Finally, NASA and ISLSCP are interested in such a project in Sahel.

4 - PROJECT SCHEDULE

In 1989, all the data about the Niamey square degree will be collected. Different calls for an international collaboration with others Laboratories and Institutes working in the same domains of researchs will be issued in workshops and meetings concerning both hydrologic and meteorological sciences.

In 1990 and 1991, tools and scientific equipments will be brought together again in the aim to carry out in 1992, terrain measurements in good conditions with airborne operations.

NASA staff will participate at these operations.

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ABREVIATIONS, SIGLES ET ACRONYMES

ABBREVIATIONS & ACRONYMS

1 – INSTITUTIONS & PROGRAMMES

AGRHYMET Niamey : Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle (interafricain)

ASECNA Dakar : Agence pour la Sécurité de la Navigation Aérienne (interafricain)

BRGM Orléans : Bureau des Recherches Géologiques et Minières (France)

CEE Bruxelles : Communauté Economique Européenne (en anglais EEC)

CESR Toulouse : Centre d'Etude Spatiale des Rayonnements (France)

CIEH Ouagadougou : Centre Interafricain d'Etudes Hydrauliques (interafricain)

CILSS Ouagadougou : Comité Permanent Interétats de Lutte contre la Sécheresse dans le Sahel (interafricain)

CNES Toulouse : Centre National d'Etudes Spatiales (France)

CNRM Toulouse : Centre National de Recherches Météorologiques (France)

DMSP : Defence Meteorological Satellite Programme

ESA : European Space Agency

FAO Rome : Food & Agricultural Organization

GDTA Toulouse : Groupement pour le Développement de la Télédétection Aérospatiale (France)

GSTS Strasbourg : Groupement Scientifique de Télédétection Spatiale (France)

ICRISAT Centre Régional Niamey : International Crops Research Institute for the Semi-Arid Tropics (International)

ICSU : International Council of Scientific Unions

IGBP : International Geosphere Biosphere Programme

IH Wallingford : Institute of Hydrology (Grande-Bretagne)

INRA Paris : Institut National de la Recherche Agronomique (France)

INRAN Niamey : Institut National de Recherches Agronomiques du Niger

INSU Paris : Institut National des Sciences de l'Univers (France)

IRAT Paris : Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières (France)

IRI Niamey : Institut des Radio-Isotopes (Niger)

LAMP Clermont-Ferrand : Laboratoire de Météorologie Physique (France)

LERTS Toulouse : Laboratoire d'Etudes et de Recherches sur la Télédétection Spatiale (France)

LMD Palaiseau : Laboratoire de Météorologie Dynamique (France)

LSIT Strasbourg : Laboratoire des Sciences de l'Image et de la Télédétection (France)

NASA Washington : National Aeronautics & Space Administration (USA)

NOAA Washington : National Oceanic & Atmospheric Administration (USA)

OMM Genève : Organisation Météorologique Mondiale (WMO en anglais)

OPGC Clermont-Ferrand : Observatoire de Physique du Globe de Clermont-Ferrand (France)

ORSTOM Paris : Institut Français de Recherche Scientifique pour le Développement en Coopération (France)

PNEDC : Programme National d'Etude de la Dynamique du Climat (France)

PNUD New York : Programme des Nations Unies pour le Développement (UNDP en anglais)

PNUE Nairobi : Programme des Nations Unies pour l'Environnement (UNEP en anglais)

UNDP New York : United Nations Development Programme (PNUD en français)

UNEP Nairobi : United Nations Environment Programme (PNUE en français)

UNESCO Paris : Organisation des Nations Unies pour l'Education, la Science et la Culture

WCAP : World Climate Applications Programme

WCDP : World Climate Data Programme

WCISP : World Climate Impact Studies Programme

WCRP Genève : World Climate Research Programme (OMM/WMO)

WMO Genève : World Meteorological Organization (OMM en français)

2 - AUTRES - OTHER

ABL : Atmospheric Boundary Layer

AVHRR : Advanced Very High Resolution Radiometer des satellites NOAA

BEARN : Bilan d'Energie Automatique Régional Numérisé

ECLATS : Etude de la Couche Limite Atmosphérique Tropicale Sèche

EPSAT : Estimation des Précipitations par Satellite

ETR : Evapotranspiration Réelle

FIFE : First ISLSCP Field Experiment (Konza Prairie, Kansas, USA)

GCM : General Circulation Model

GOES : Geostationary Operational Environmental Satellite

HAPEX : Hydrologic and Atmospheric Pilot Experiment

IR : Infra-Rouge (canal infra-rouge)

IRT : Infra-Rouge Thermique

ISLSCP : International Satellite Land Surface Climatology Project (International)

MOBILHY : Modélisation du Bilan Hydrique

MOS : Meteorological Observation Satellite

PATAC : Prévision Améliorée, Technique d'Affinement de la Climatologie

PBMR : Push Broom Macrowave Radiometer

SAMER : Station Automatique de Mesure de l'Evaporation Réelle

SIB : Simple Biosphere Model

SMMR : Scanning Multichanel Microwave Radiometer

SPOT : Système Probatoire d'Observation de la Terre (satellite français)

SSM/I : Special Sensor Microwave Imager

ST : Strato-Troposphère

TAMSAT : Tropical African Meteorological Satellite

TIMS : Thermal Infrared Microwave Spectrometer

TM : Thematic Mapper

TU : Temps Universel

UHF : Ultra High Frequency

CLIMATOLOGY

. **Wind**

	< 6 km/h	6 to 25	26 to 50	> 50
rainy season	15	83	2	0
dry season	17	80	3	0

. **Température**

T = 28°9
(Tx_{max} = 41°4 (april)
(Tx_{min} = 31°5 (august)

(TN_{max} = 27°3 (may)
(TN_{min} = 15°5 (january)

. **Hygrometry**

(U_X = 62% (31 in march, 94 in august)
(U_N = 26% (8 in february, 60 in august)

. **Evaporation** (Colorado pan)

(Tin Adjar : 3200 mm
(M'Bouna : 2500 mm
(Iferouane : 4000 mm

. **Rainfall**

- Annual
  (Ten-years wet 760 mm
  (Ten-years dry 420 mm

- Monthly

J	F	M	A	M	J	J	A	S	O	N	D
0	0	2	7	32	80	148	207	94	15	1	0

- Daily
  (annual 50 mm
  (ten-years 90 mm
  (hundred-years 120 mm.

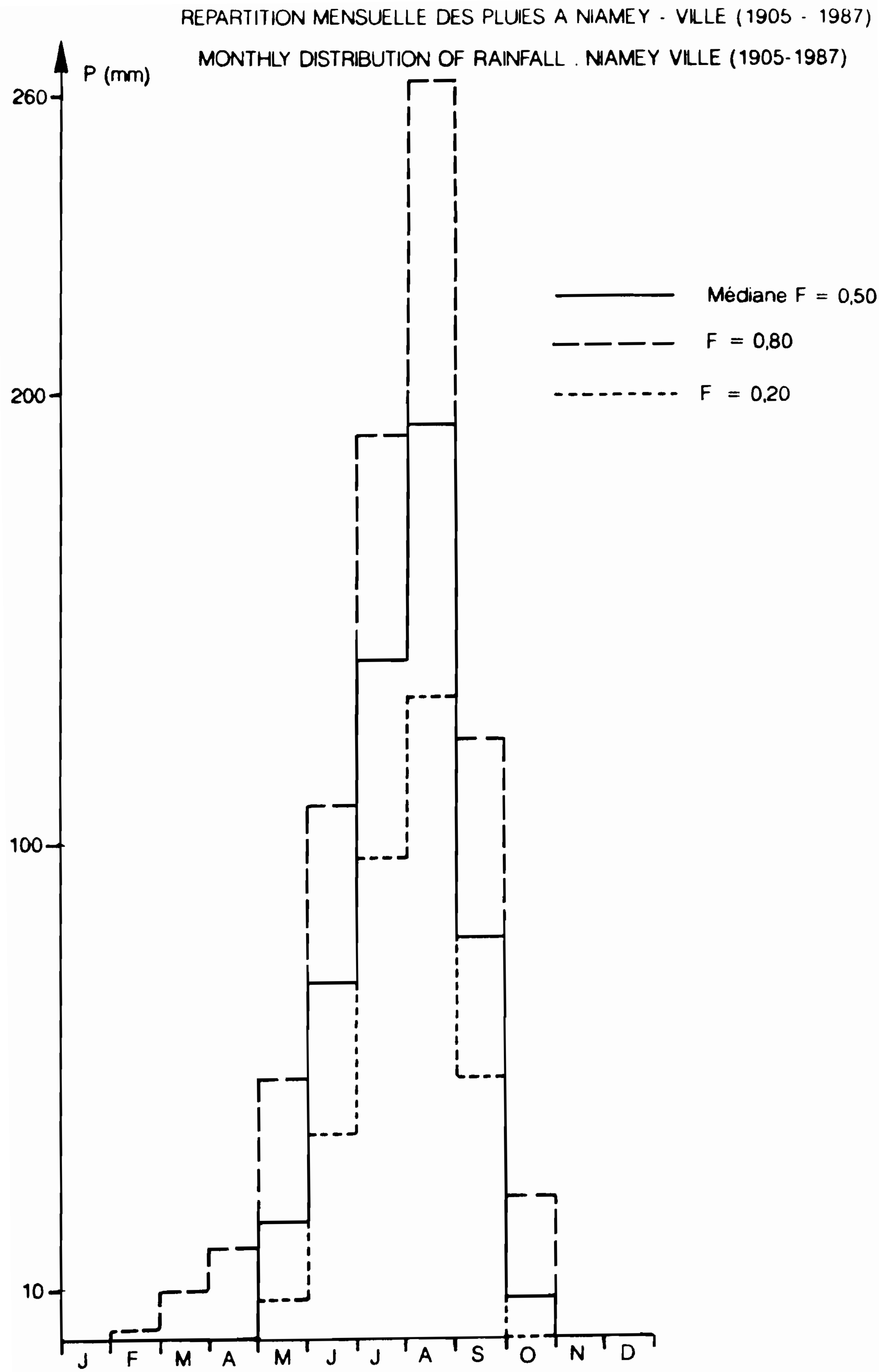

REPARTITION MENSUELLE DES PLUIES A NIAMEY - VILLE (1905 - 1987)
MONTHLY DISTRIBUTION OF RAINFALL . NIAMEY VILLE (1905-1987)
P (mm)
260
200
100
10
Médiane F = 0,50
F = 0,80
F = 0,20
J
F
M
A
M
J
J
A
S
O
N
D

Fig. 1

HAPEX-SAHEL

Le site du projet - Réseau routier

PROJECT AREA ROAD NETWORK

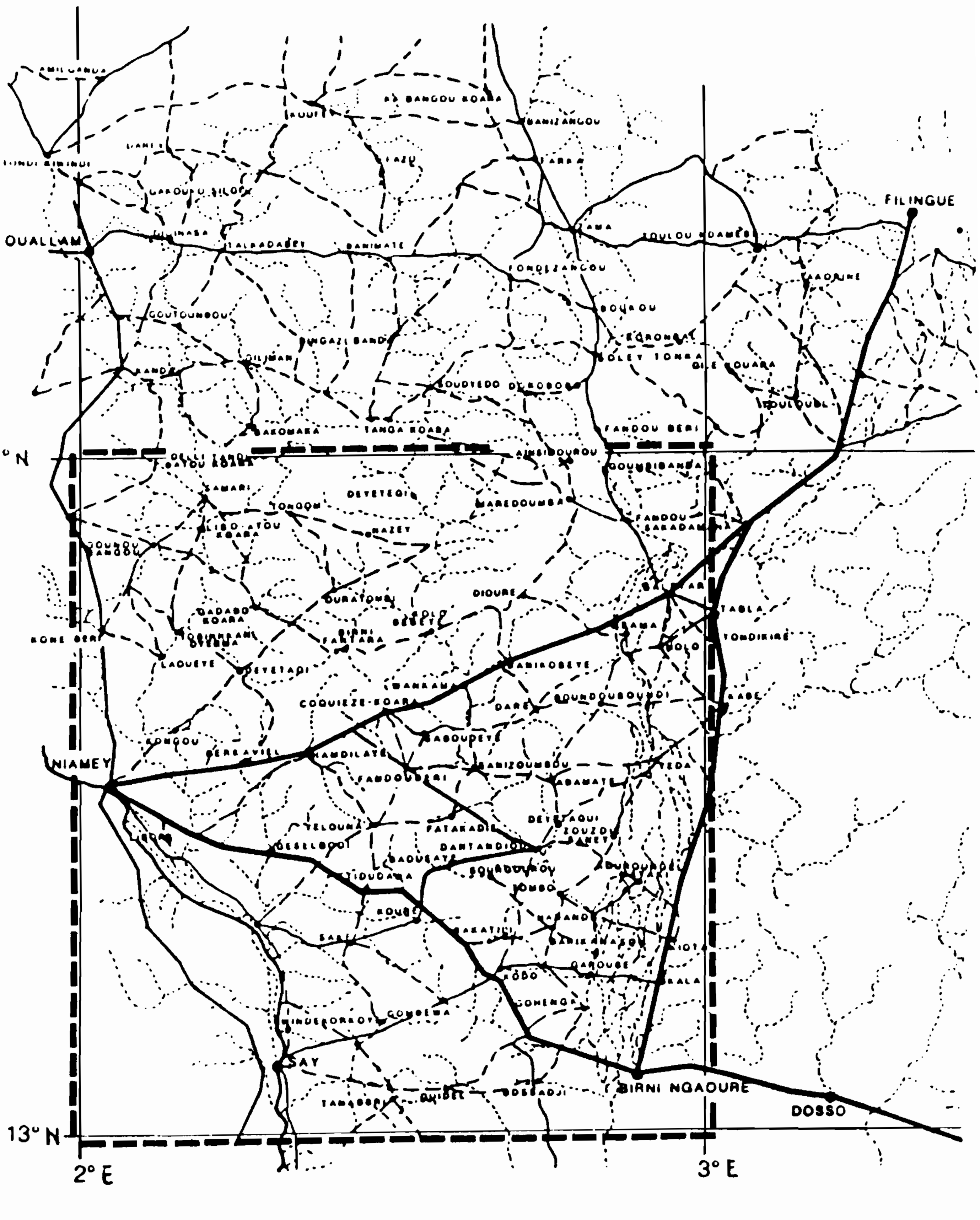


Fig.2

10 km

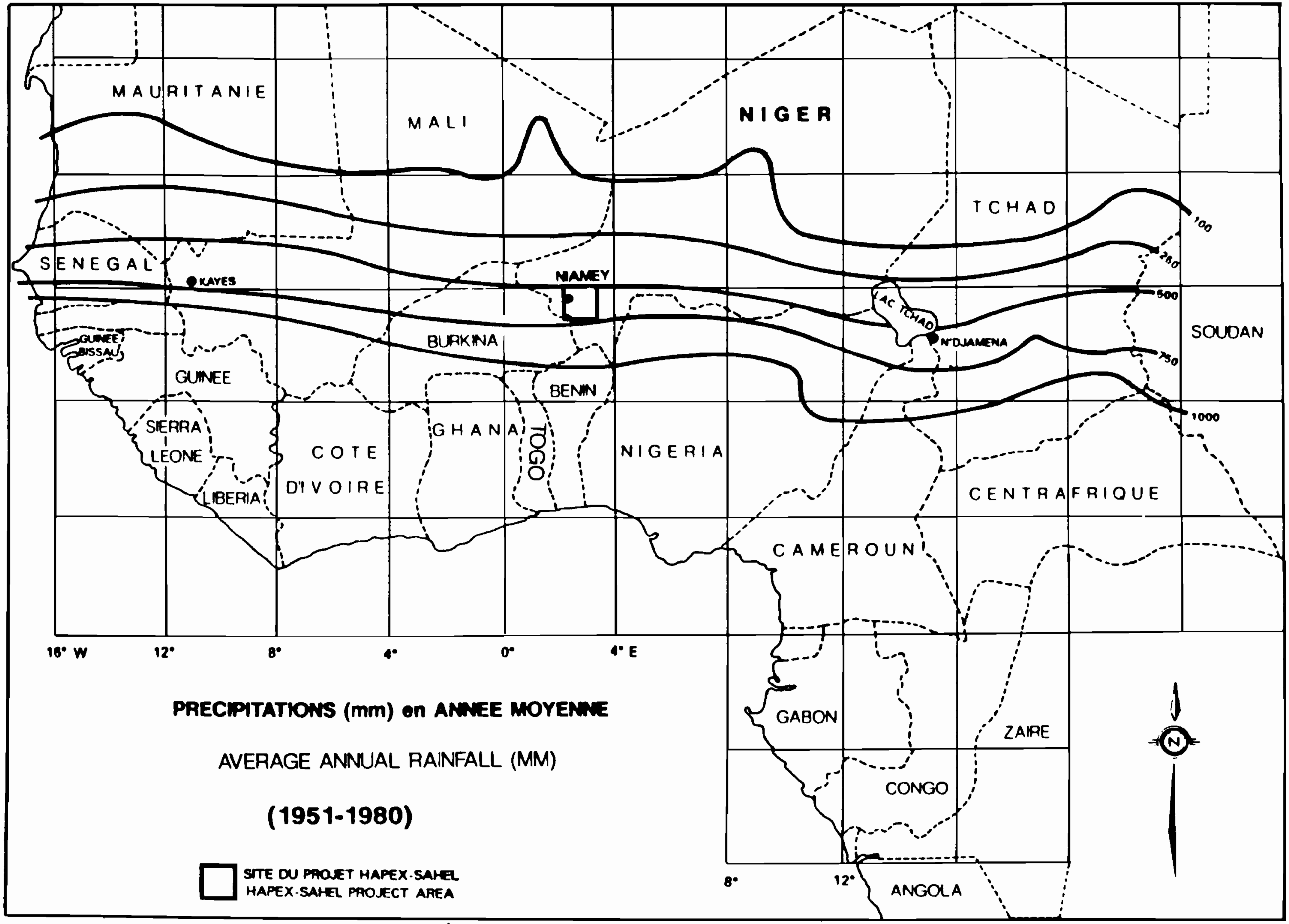

MAURITANIE
MALI
NIGER
TCHAD
SENEGAL
KAYES
NIAMEY
LAC TCHAD
N'DJAMENA
SOUDAN
GUINEE BISSAU
BURKINA
GUINEE
BENIN
SIERRA LEONE
COTE D'IVOIRE
GHANA
TOGO
NIGERIA
LIBERIA
CENTRAFRIQUE
CAMEROUN
GABON
ZAIRE
CONGO
ANGOLA
100
250
500
750
1000
18°
14°
10°
6°
2° N
16° W
12°
8°
4°
0°
4° E
8°
12°
N
PRECIPITATIONS (mm) en ANNEE MOYENNE
AVERAGE ANNUAL RAINFALL (MM)
(1951-1980)
SITE DU PROJET HAPEX-SAHEL
HAPEX-SAHEL PROJECT AREA

Fig.3

CARTE GENERALE DES SOLS DE L' AFRIQUE DE L' OUEST

GENERAL MAP OF SOILS OF WEST AFRICA

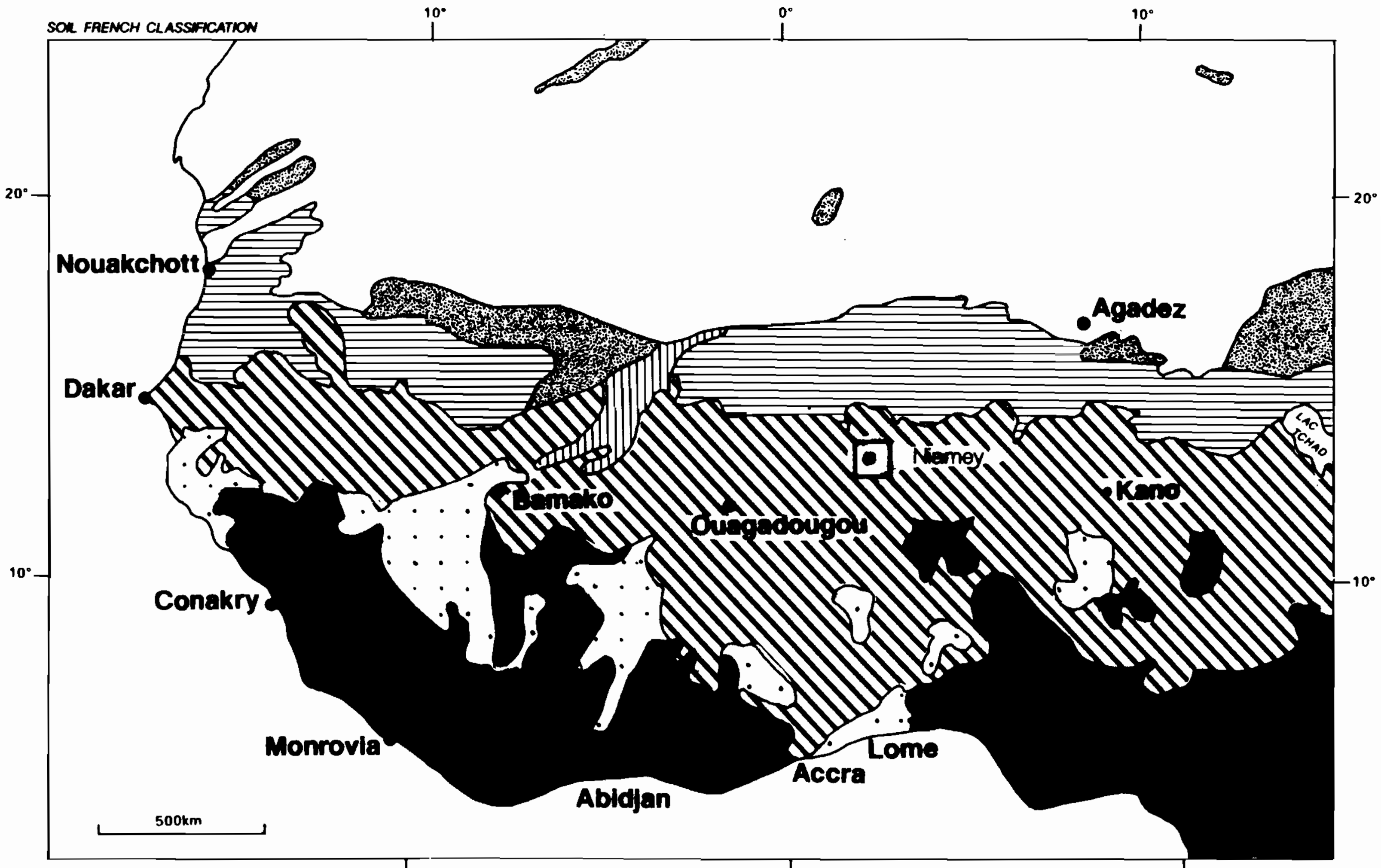


Fig.-4-

Mineral soils of the deserts

None developped subdesertic soils

Hydromorphic soils

Ferruginous tropical soils

Ferralitic soils

Isohumic soils

Ferruginous tropical and ferrallitic soils association

HAPEX-SAHEL project location

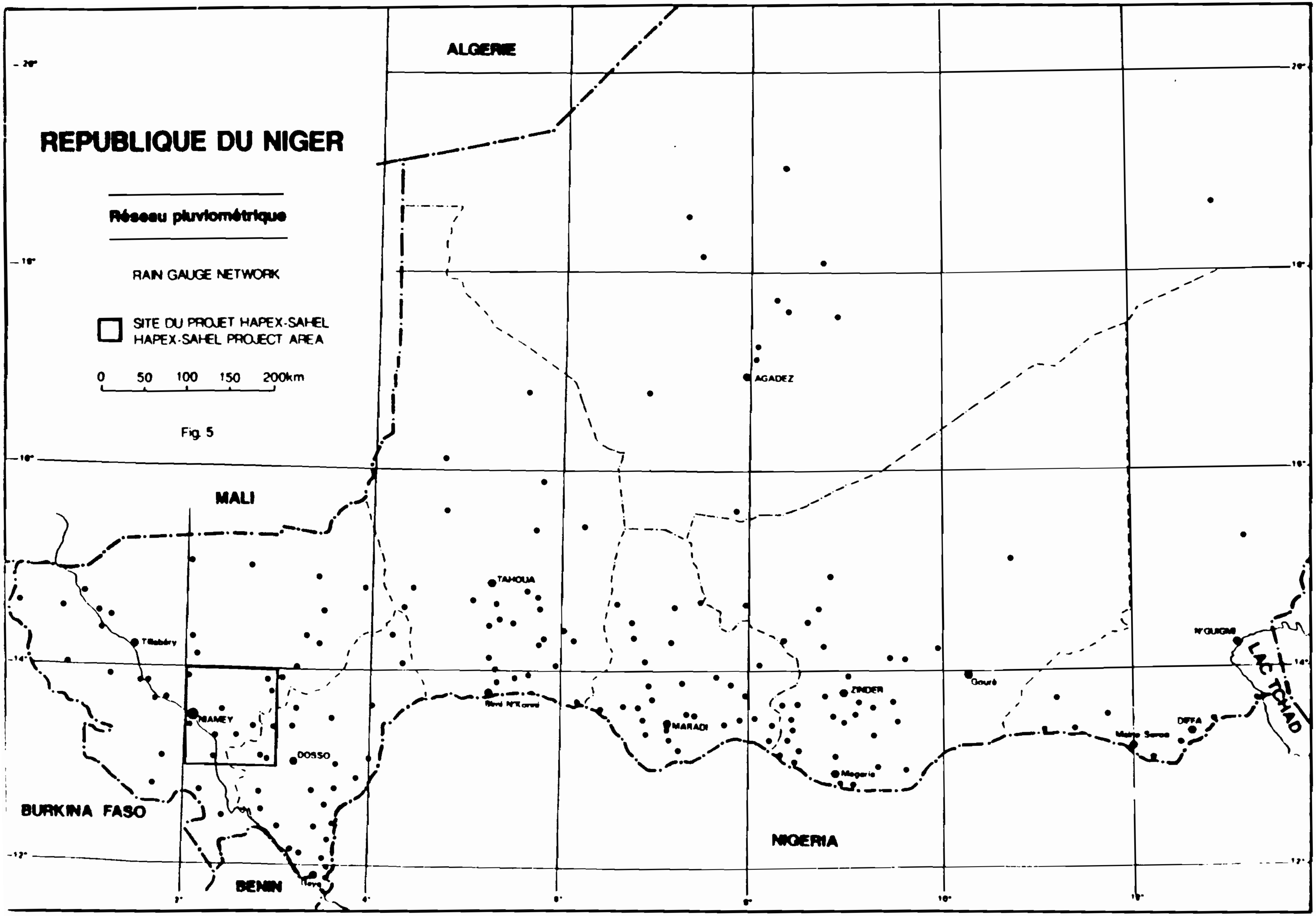

ALGERIE
REPUBLIQUE DU NIGER
Réseau pluviométrique
RAIN GAUGE NETWORK
SITE DU PROJET HAPEX-SAHEL
HAPEX-SAHEL PROJECT AREA
0 50 100 150 200km
MALI
AGADEZ
TAHOUA
Tillabéry
NIAMEY
DOSSO
MARADI
ZINDER
Gouré
N'GUIGMI
LAC TCHAD
DIFFA
Magaria
BURKINA FASO
BENIN
NIGERIA

Fig. 5

PROJET DE MESURE DES ECOULEMENTS DE SURFACE

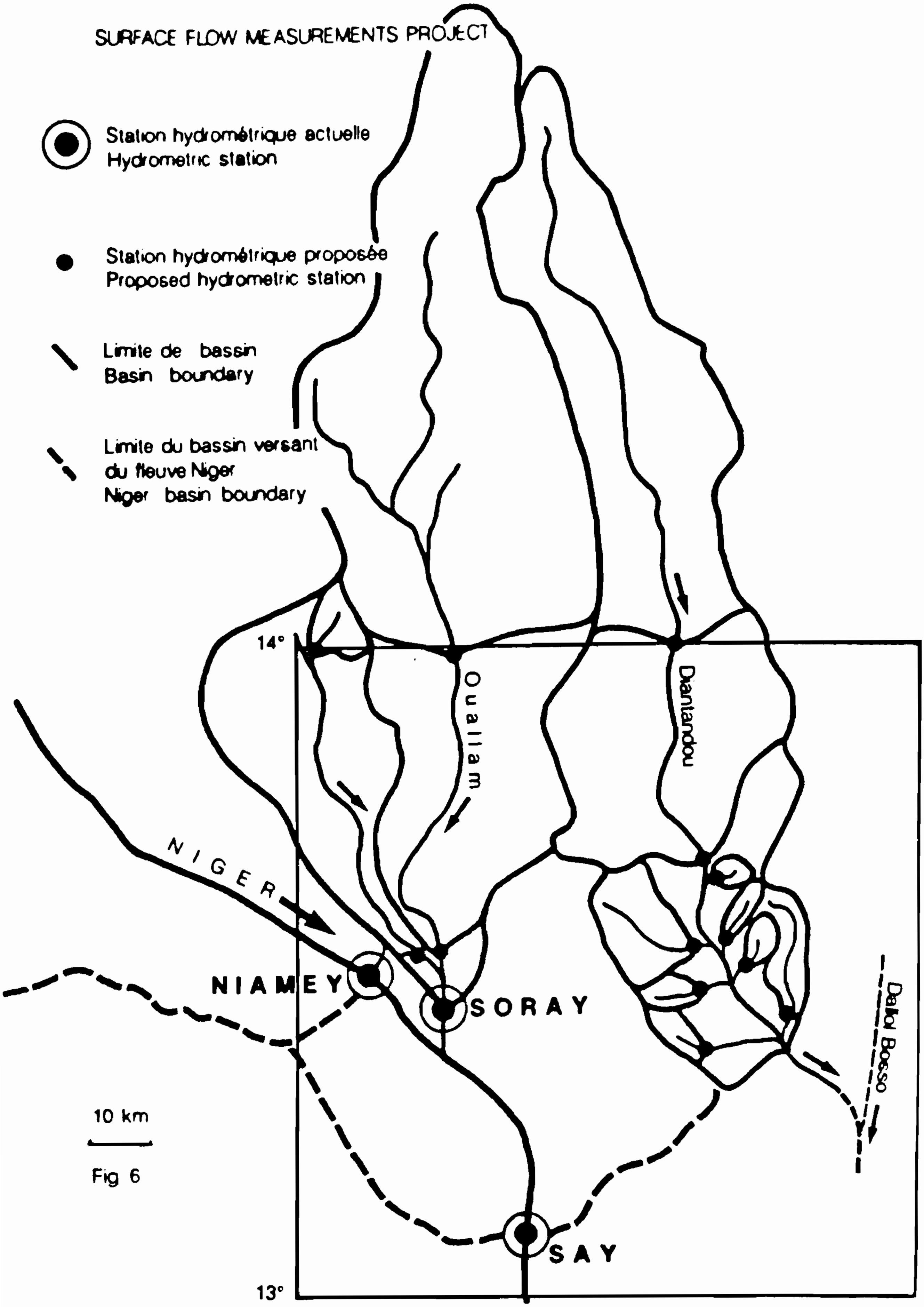


Fig 6

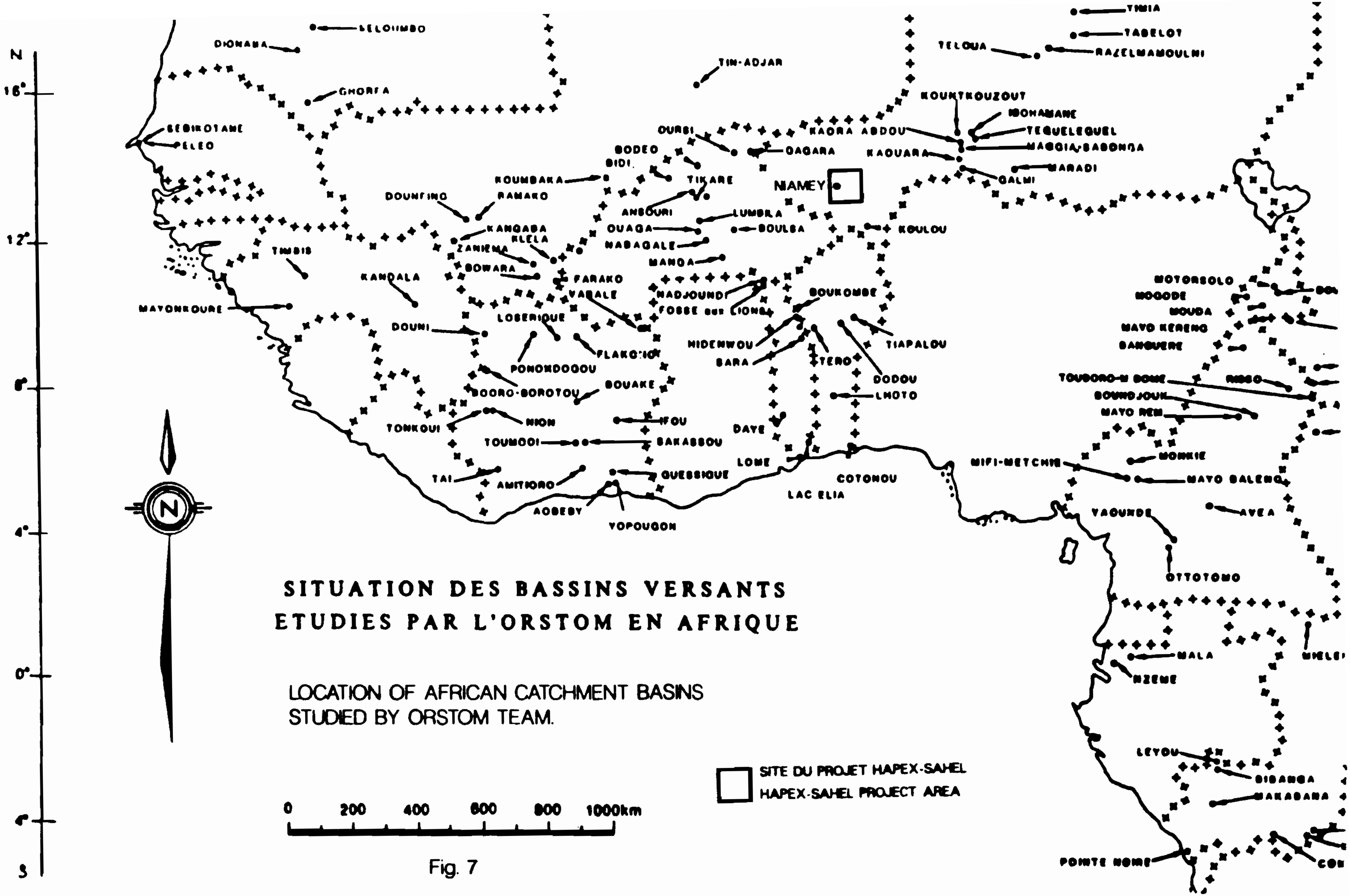
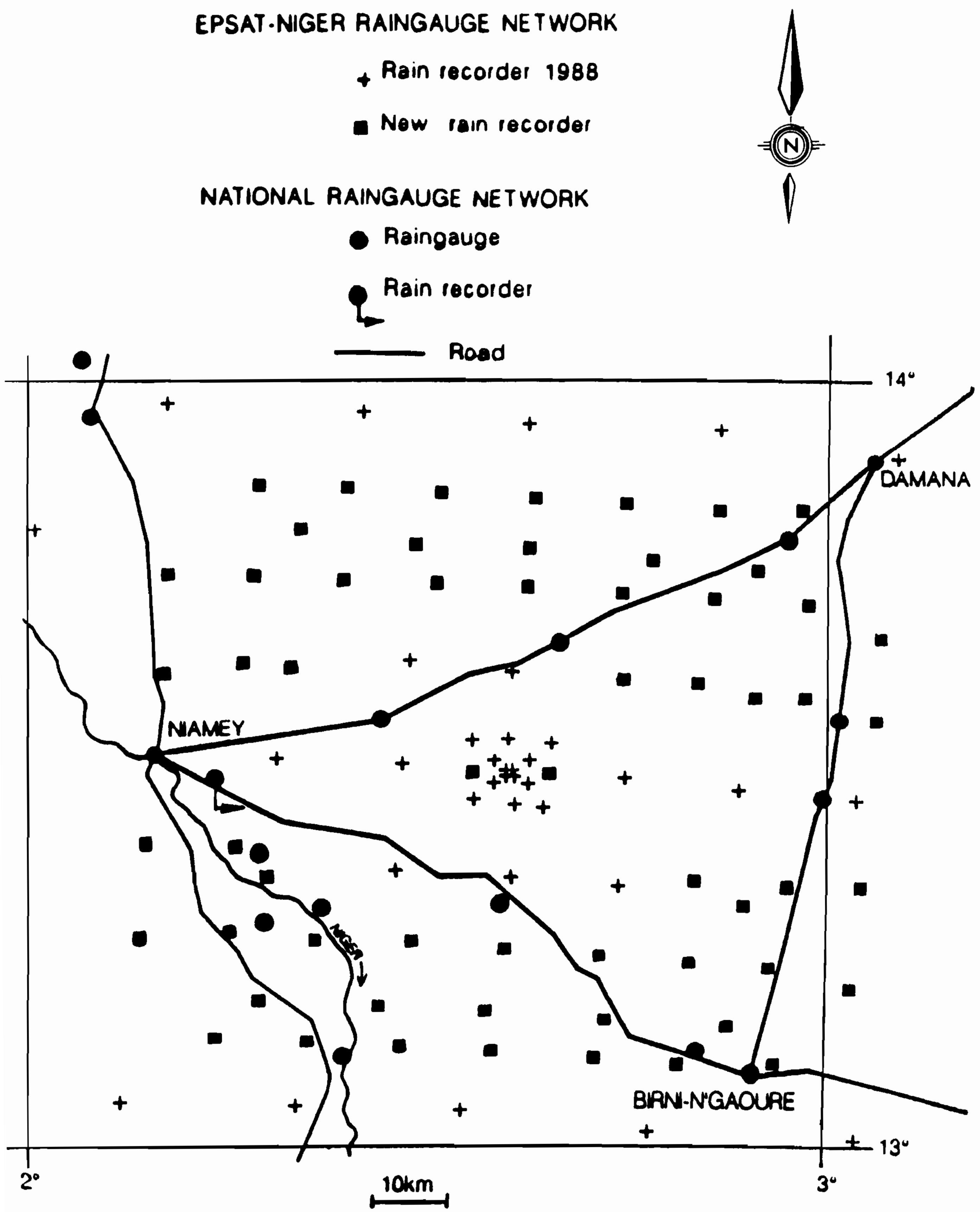

N
16°
12°
8°
4°
0°
4°
S
DIONAMA
SELOUMBO
GHORFA
SEBIKOTANE
PELEO
TIMBIS
MAYONKOURE
DOUNFING
RAMAKO
KOUMBAKA
KANGABA
KLELA
ZANIENA
BOWARA
KANDALA
DOUNI
LOBERIQUE
FARAKO
VARALE
PONONDOUGOU
FLAKOHO
BOORO-BOROTOU
BOUAKE
TONKOUI
NION
TOUMODI
SAKASSOU
IFOU
TAI
AMITIORO
QUESSIQUE
AOBEBY
YOPOUGON
TIN-ADJAR
OURSI
GAGARA
BODEO
BIDI
TIKARE
ANSOURI
LUMBILA
OUAGA
BOULSA
NABAGALE
MANGA
NADJOUNDI
FOSSE aux LIONS
BOUKOMBE
NIDENWOU
BARA
TERO
TIAPALOU
DODOU
LHOTO
DAYE
LOME
COTONOU
LAC ELIA
KOULOU
NIAMEY
TELOUA
TIMIA
TABELOT
RAZELMAMOULNI
KOUNTKOUZOUT
IBOHAMANE
KAORA ABDOU
TEQUELEQUEL
MAGGIA-BABONGA
KAOUARA
MARADI
GALMI
MOTORSOLO
MOGODE
MOUDA
MAYO KERENG
BANGUERE
TOUBORO-N DOME
BOUNDJOUK
MAYO REM
MIFI-METCHIE
MONKIE
MAYO BALENG
YAOUNDE
AVEA
OTTOTOMO
MALA
NZEME
LEYOU
BIBANGA
MAKABANA
POINTE NOIRE
SITUATION DES BASSINS VERSANTS
ETUDIES PAR L'ORSTOM EN AFRIQUE
LOCATION OF AFRICAN CATCHMENT BASINS
STUDIED BY ORSTOM TEAM.
SITE DU PROJET HAPEX-SAHEL
HAPEX-SAHEL PROJECT AREA
0
200
400
600
800
1000km

Fig. 7

Fig. 8


EPSAT-NIGER RAINGAUGE NETWORK
Rain recorder 1988
New rain recorder
NATIONAL RAINGAUGE NETWORK
Raingauge
Rain recorder
Road
N
14°
13°
2°
3°
DAMANA
NIAMEY
NIGER
BIRNI-N'GAOURE
10km