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Hydrology in Africa

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INTRODUCTION

The object of this critical study is to provide a general review of present knowledge concerning the hydrology of the whole of the African continent. Little specific information is given on the hydrological characteristics of individual river basins. For such information the reader is referred to the works mentioned in the bibliography at the end of this study.

Any real assessment of the state of hydrological research in the different parts of Africa can only be made in relation to local conditions and requirements.

Natural conditions are so varied and degrees of economic development differ so widely that comparisons are not always possible. The organization of a hydrometrical network, which is relatively easy in the temperate zones, becomes almost impossible in the zone situated between the desert and tropical regions.

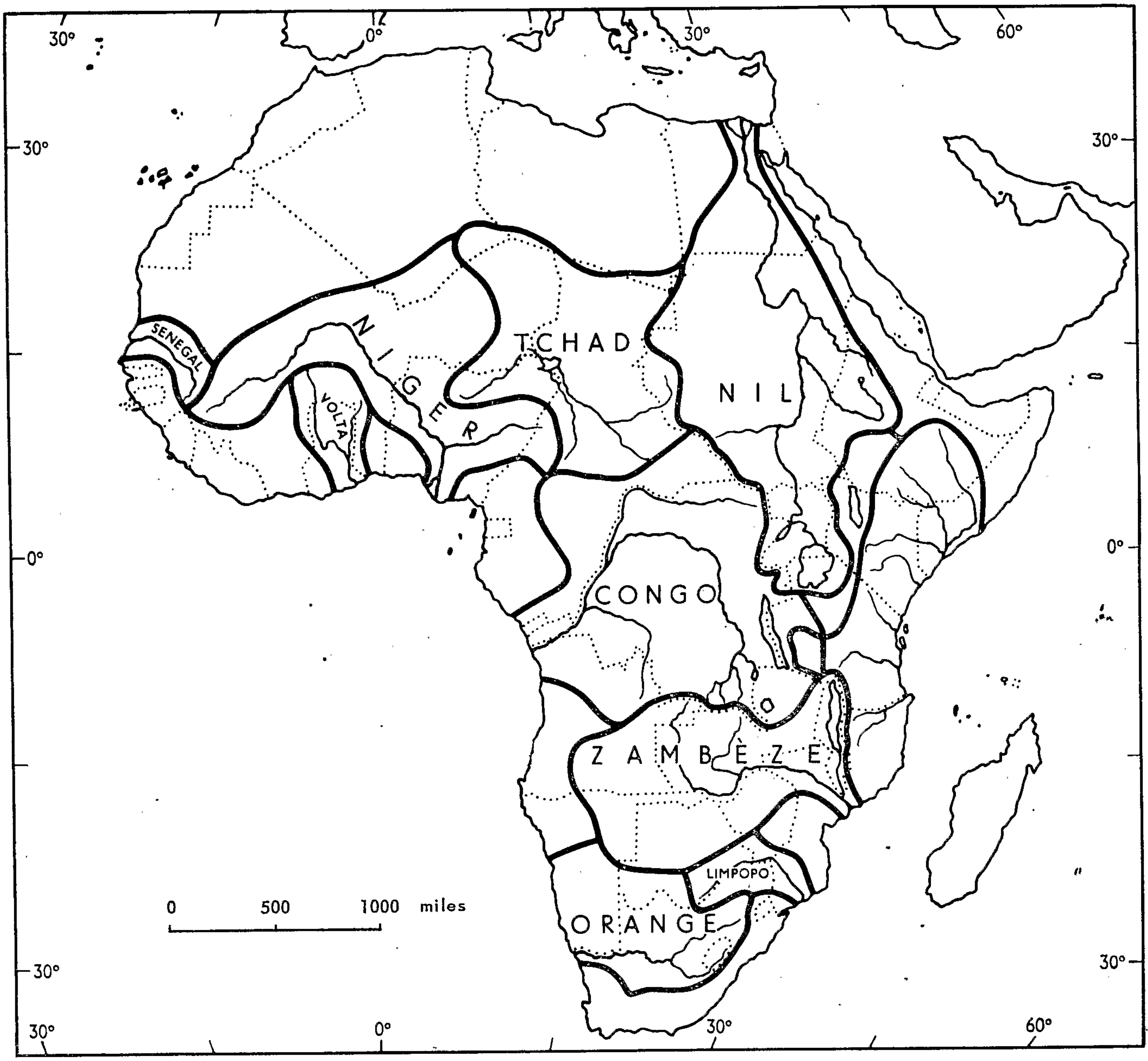
While the study of certain branches of hydrology may be of very little importance in certain territories, it may well be essential in others. For example, the amount of research done on surface run-off in the desert is negligible, since this is an exceptional phenomenon in such areas. On the other hand, hydrogeological studies, which are only slightly developed in the area of West Africa where the crystalline base crops out, are well advanced in the arid or semi-arid regions of sedimentary formation. The measurement of water salinity is hardly necessary at the head of the Gulf of Guinea, where the rainfall is abundant and the water very soft, but in East Africa the scarcity of water and the need for irrigation make it an essential and normal activity.

For this reason it may be as well, before going any further, to outline the conditions under which hydrological studies are carried out in the various zones. These conditions can be grouped under three headings: climate, communication facilities and the local availability of competent staff.

First of all, Africa may be divided roughly into climatic belts following the parallels of latitude; this is particularly the case north of the equator. The coastal areas of North Africa have a Mediterranean climate, with a well-defined period of drought in summer and a long period of somewhat irregular rainfall from September to May. The maximum precipitation is just as likely to be recorded in November as in March. Road communications are good, the population density is relatively high and the standard of education is also fairly high. All these are factors which favour the development of hydrological studies, and since water supplies can be used for productive farming it is only normal that considerable financial resources should be made available for hydrological survey. Unfortunately, however, the frequent shifting of watercourses and the irregularity of the flow of water make the work of interpreting measurements extremely difficult. There is a great deal of erosion, the water is often salty and underground waters are frequently abundant.

Towards the south the climate becomes more and more arid. The Mediterranean regions give place to the Sahara desert, which extends from the Atlantic to the Red Sea, broken only by the Nile valley, the lower part of which, in Egypt, is in many ways similar to the zone described above. Much of the Sahara is complete desert. Rain is very rare. It may fall at any time of the year except in the extreme south where it occurs only during the northern summer. Surface run-off is of very short duration and occurs only in the more favoured zones. On the other hand, however, the sedimentary rock may contain considerable reserves of underground water. Losses by evaporation are extremely high. The climatic conditions are exacting and the sparsity of the population and the difficult travelling conditions render observations of every kind extremely difficult.

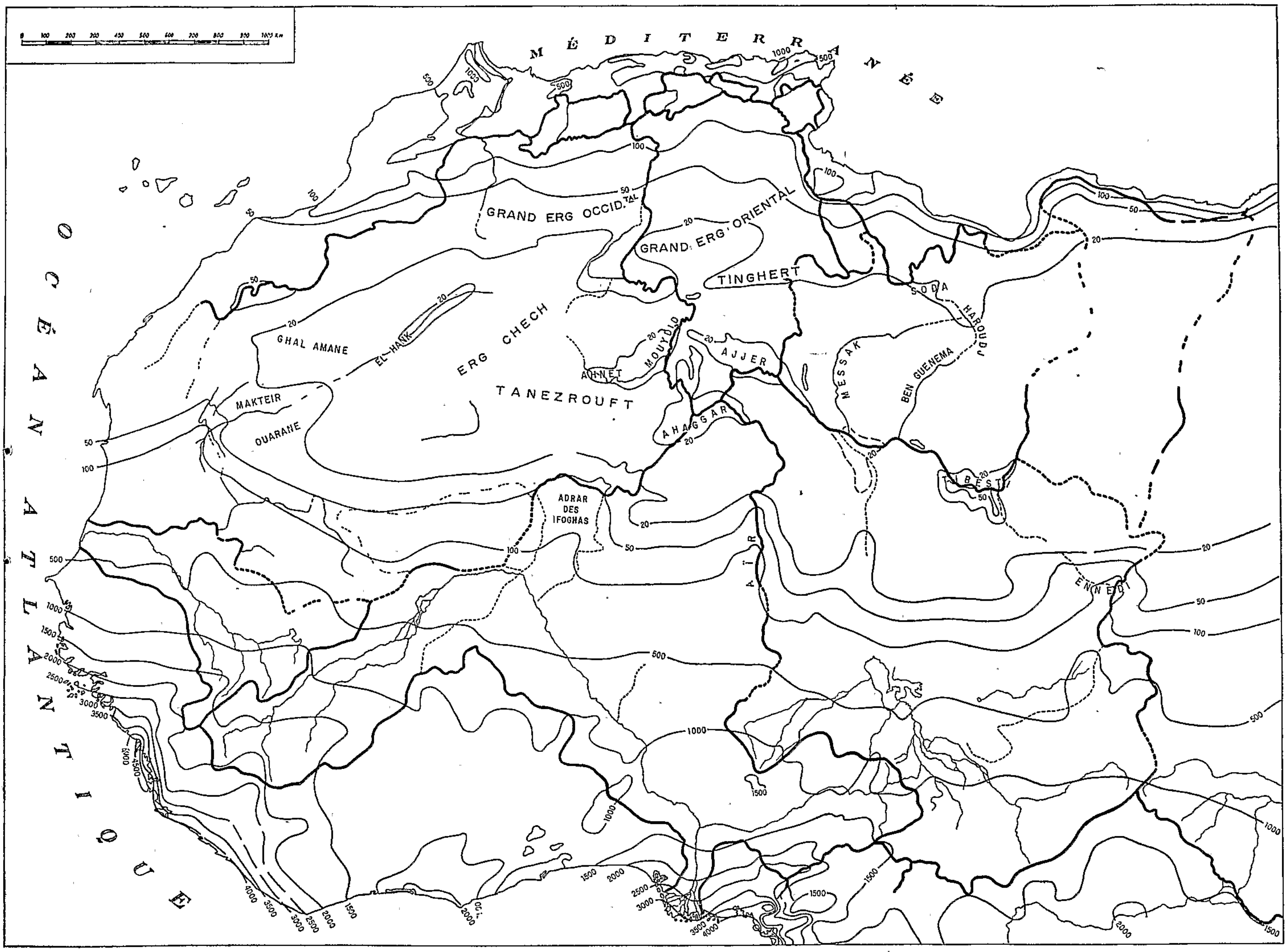
The region immediately south of the Sahara is known to hydrologists as the Sahelian zone. It is a region of climatic contrasts; the nine months of almost complete drought from October to June are followed by a rainy season which transforms the greater part of the region, where the relief is in general fairly low, into swamps. The run-off, which is torrential, unpredictable and frequently concealed, presents the hydrologist with a number of perplexing problems. Travel during the rainy season, which is when observations have to be made, can be a very trying experience for the hydrologist, who usually prefers to work in the desert.



Map of the main catchment areas in Africa [from D.O.S. (Misc.) 230/4]

Chief rivers

Approximate limits of the major catchment areas



Map of the main catchment areas of North and West Africa. Mean annual rainfall (mm.), 1926-50 (from *Reviews of Research on Arid Zone Hydrology*, Paris, Unesco, 1953)

The characteristically tropical regions, which lie south of a line running from Dakar to Cape Guardafui, have a typical hydrographic system. These regions are traversed by great rivers—the Senegal, Niger, Volta, Sanaga, Shari and the principal tributaries of the Nile—which have clearly a uniform régime: a rainy season from May or June to September or October, followed by a distinct dry season. In the west the annual rainfall is abundant, exceeding 2,000 mm. in some parts. Further east it decreases fairly regularly to 900 mm. in the Nile basin. It increases again on the slopes of the Ethiopian highlands and then decreases very rapidly towards the eastern extremity of Africa where the climate becomes semi-arid, and even arid on the coast, with annual precipitations of only 100 mm.

Despite the vast extent of this zone there is very little variation in geological conditions. One often finds, especially in the west, the old granite gneissic shelf and the pre-Cambrian metamorphic terrains or the cover of Ordovician sandstone. In the first of these cases there is no possibility of finding deep underground reserves, and in the second case very little possibility. Towards the east, on the contrary, the terrains are much more varied and volcanic and sedimentary zones occur with some substantial underground water reserves.

In general the ordinary régime is easily traced, and communications are not difficult except in the most easterly third of this zone, where swamps and mountains are often insurmountable obstacles. In many regions it is difficult to train competent observers.

Typically, the equatorial régions have two dry seasons and two rainy seasons. These regions are situated along the south coast of West Africa, south of the Cameroon Republic, in the Ogowe Basin, the greater part of the Congo Basin, the extreme north of Angola, the principal branches of the Nile, the greater part of the Great Lakes and the coast of Kenya and Tanganyika (except the extreme south). The rainfall pattern varies considerably. The coastlands of the Gulf of Guinea, many parts of which have an annual precipitation of more than 3,000 mm. a year, have practically no dry season, whereas the annual figure for certain places in east Kenya is no more than 250 mm. with a dry season which often lasts almost the whole year.

These variations are frequently observed within quite limited areas, especially around Lake Tanganyika, where, according to their orientation, heavily forested mountains alternate with valleys covered with thorny vegetation. Permeable areas such as the sedimentary zones of the Congo Basin or the volcanic zones of the rift valleys are much more numerous than in the tropical regions.

The variations in the average discharge of the rivers are even more pronounced than those in the annual amount of rainfall.

Generally speaking, hydrological knowledge of the equatorial regions is limited mainly because of the recent date of exploration of these regions, the very great difficulty experienced in recruiting observers and the poor communications.

South of the equatorial régime towards the northern limits of the Zambezi, the southern limits of the Congo Basin, Lake Nyasa and south of the Tanganyika Territory, the tropical régime is found once again. In the most northerly districts there is a rainy season from November to April and a dry season of equal duration. Towards the south the rainy season becomes shorter. In general the annual rainfall increases from the west coast, which is semi-arid or arid, towards the east where the pattern of isohyets is much less simple than in the northern hemisphere. In particular, the east coast is fairly well watered down to the southern extremity of Africa; even in the latitudes between 20 and 30 degrees, the northern counterpart of which is around Rio de Oro, the rainfall is more than 1,000 mm. a year. As against this, in the centre of southern Africa the precipitation decreases from north to south, and is as little as 100 mm. in the Kalahari desert. One then encounters the intermediary régimes similar to those in the northern tropical region, from the Guinean régime in Katanga to the desert régime, including the zone of hydrographic degradation. In these regions as in the preceding zone the variations in land relief have a great effect on precipitation.

In the Kalahari desert, studies of any kind are extremely difficult to carry out. On the other hand, further eastward, in the territories from south of the Zambezi to Cape Province, the degree of economic development increases as one travels south, communications are easier and the recruitment of observers is no longer an insoluble problem.

Finally the southern extremity of Africa has a Mediterranean climate with a full winter season in the south-east and rains distributed throughout the year in the south. In the eastern part of South Africa a gradual transition of the rainfall pattern is to be observed, from a short regular rainy season in the north, to irregular distribution throughout the whole year, with summer rains predominating, in the south. Throughout the territory of South Africa the geological structure varies considerably. Sedimentary formations are frequent and hydrogeological research is thus of great importance—which further emphasizes the general similarity of these regions to those of North Africa.

The broad climatic zones briefly outlined above will provide the main headings for the critical study which follows. While such classifications are not always easy to establish they are infinitely superior to those based on territorial boundaries which, since they are often artificial, are unsuitable for our present purposes.

NORTH AFRICAN MEDITERRANEAN REGIONS

These are essentially the moist and semi-arid regions stretching from the Atlantic Ocean along the Mediterranean through Morocco, Algeria, Tunisia and Libya. This zone, which is bounded on the south and the east by the desert, gradually narrows from west to east.

The relatively dense rain-gauge network of the whole area, which has been observed over a fairly long period, allows us to trace a pattern of isohyets which is sufficient for an estimate of the rainfall on the larger and medium catchment basins. But in most of the very hilly regions the number of stations is insufficient to provide information for a study of the run-off of the smaller basins. Furthermore, because of the disturbed conditions which have obtained in certain areas, there are considerable gaps in the information available.

The fact that a number of dams have been built in these regions accounts for the early establishment of hydrological surveys and hydrometrical networks. The hydrometrical networks in the zone with an annual rainfall of more than 200 to 250 mm. show the following characteristics.

MOROCCO

Some forty stations have been set up including twenty which are well calibrated; this corresponds to a density of one station of the latter type for every 9,000 sq.km., which is not very much for a country where the prospects for economic development are extremely promising and where the question of water supply is so essential.

The longest continuous observation period goes back to 1924 but the majority of the main stations were in regular operation in 1935. The system was completed in 1948-49 by the Hydrological Service. Some isolated data for as far back as 1912 are also available.

It is obvious that the observation periods are too short, and this is a difficulty we shall encounter to an even greater degree in many other regions of Africa.

ALGERIA

The data from some forty stations where calibration has been made possible by means of gauging channels are published in the *Annuaire Hydrologique*. There is thus one station for every 3,000 sq.km., which, though better than the situation in Morocco, is still far from adequate.[1] However, detailed studies of the river basins, both from the point of view of the hydrological system and from the point of view of climate and other factors, make it possible to work out formulae for run-off on the basis of which interpolations can be made.

As in the case of Morocco the observation periods are too short in view of the very irregular character of the régime. Some stations have been worked regularly since 1924 and observations for one are available for as far back as 1911; but most of the main stations have been in service only since 1949-50. A few isolated data before the 1923-25 period yield valuable supplementary information.

TUNISIA

The zone with an annual precipitation exceeding 300 mm. is much smaller here than in Algeria but the density of the principal gauging stations is the same: one for every 3,000 sq.km. Considerable efforts have been made to set up permanent and well-calibrated gauging stations on the difficult local watercourses. The remarks made concerning observation periods in the territories mentioned above apply here also. Deficiencies in the basic network can largely be made up by systematic base flow studies.

Unfortunately few studies of experimental basins have been carried out.

In Morocco, Algeria and Tunisia flow data for the main stations are published regularly in hydrological yearbooks and similar documents.

LIBYA

The semi-arid climatic zone is even less extensive in Libya than in Tunisia and this precludes the possibility of setting up a proper hydrometric system. Nevertheless measurements of flow and studies of run-off have been carried out in some wadis.

In all these territories considerable progress has been made with hydrogeological studies, especially in Tunisia where water needs greatly exceed the surface resources. Systematic studies have been made of data obtained from geological, cartographical and contour surveys—all of which are of fundamental importance for this type of research. A good deal of work has been done on the cataloguing of the water points in Algeria, Morocco and Tunisia. The characteristics of the principal underground aquifers are now generally fairly well known as the result of a sustained programme of borings and geophysical prospecting. These include the aquifers of the Great Plains in Morocco, the low sublittoral plains of Algeria and the high Algerian plains, the captive underground waters of the basins on the high plains of Algeria, the water-bearing strata of various formations in the folded regions of Tunisia, the artesian waters of the down-thrown areas which are fairly frequent in the plain of northern and central Tunisia, and the aquifers in the sandstone of the Tunisian Miocene. Finally the main circulation systems which feed the shotts are now fairly well known thanks particularly to the studies carried out on the Ech Chergui Shott.

The resources thus prospected are considerable and the aquifers frequently have a discharge of several hundred litres a second, and even, in some littoral plains, of several cubic metres a second. Nevertheless a great deal of research work still remains to be done in these fairly well populated countries where water is a precious

1. At practically all the stations a great deal of channel improvement is required, in view of the instability of the stream beds and the large quantities of sediment carried. Such improvements, however, would necessitate considerable capital expenditure.

commodity that can be used quite profitably for the production of marketable goods, particularly in the vicinity of the larger markets. The tendency to misuse underground water resources is consequently widespread. The study of the replenishment of these resources and therefore of the whole question of water balance is thus of fundamental importance. So far little has been done in this direction. The plotting of the aquifers themselves is far from being completed and in Algeria and Morocco some deep aquifers have not yet even been prospected.

A question that called for careful investigation in North Africa was that of scouring, as the silting up of reservoirs has always been a problem in these countries. This means measuring not only the quantity of matter in suspension but also, if possible, the drift of stream bed deposits. The transportation of materials in streams is assessed either by observation of the sedimentation in reservoirs, which is the method generally used in Algeria, or by systematic measurement of turbidity, as practised in Tunisia.

Some important soil conservation experiments have also been carried out in these territories.

Since both surface and underground waters often contain proportions of salt that may be harmful to crops, particularly in irrigated areas, frequent and in many cases systematic water tests are carried out.

Observations to determine evaporation losses from open waters are made in many centres and attempts have even been made to study the evaporation of the waters at slight depths below the surface of the ground. Such research is of real value and much would be gained by carrying it further.

THE SAHARA AND ADJACENT REGIONS

We shall consider this zone as being bounded by the 200 mm. isohyet. Inhabitants of the Sahara would consider this figure much too high, and such a depth of rainfall would no doubt seem excessive to them. But for hydrological purposes the delimitation is a convenient one.

Except in the Egyptian part of the Nile valley, the number of rain-gauge stations is manifestly insufficient; for example, even in the 'best served' area of the central Sahara there is only one station for every 50,000 sq.km. And even then these stations, rare as they are, are located where conditions are exceptional, so that the results recorded can hardly be considered as representative. Obviously there would be little to be gained by having more stations in certain areas. But in hilly and less permeable country, where underground waters are very largely supplied by precipitation and run-off, the present network is far too scattered to allow reliable rainfall averages to be established.

It is very difficult to improve this situation, for although the difficulties of access to the rain-gauges are real the risk of theft and depredation is even greater. Nevertheless some very encouraging attempts have been made and it seems likely that for a period of several years a system of totalizators could be put into operation near one or two of the conventional rain-gauge stations. It would then be possible, by correlating other information with that supplied by such a base, to plot reliable annual rainfall curves. At the same time further investigation of rainfall intensity would be needed, since this is a factor which greatly influences run-off. At the present time a great deal of work is being done on the study of rainfall in the mountain areas of the Central Sahara.

In the Sahara, run-off is a rare phenomenon and always of extremely short duration. In the few regions where it does occur it is in fact just as torrential as the reports of local inhabitants claim. The beds of heavily eroded watercourses frequently change from one flood to the next. Gauging stations are few and far between and the installation of permanent stations is virtually impossible. Nevertheless there are two methods of gathering information which have produced useful results and which are worth particular mention.

The first is the establishment of a system of meteorological record cards which all officials on mission are required to fill in every month. These cards record information on the flooding of wadis, the duration of the flow of flood waters and the farthest point reached by the flood, which is then correlated with relevant information in existing records. By means of such observations made in areas from the Atlantic Ocean to the Nile it has been possible to determine the flooding frequencies and even to estimate the frequency at which certain volumes of flood water may be expected to occur.

The second method has been used more recently south of the Sahara but it is one that can only be applied in monsoon areas, i.e., south of the 22° parallel. A group, which includes an engineer and a trained technician, takes up a position in the mountains for the three summer months when the heavy rains occur; they set up a network of cumulative rain-gauges which are read every month, or every two months, and a number of normal gauges which are read every day. The technician stays in the locality and explores an experimental basin and, if possible, a large wadi up to a carefully selected point where he will take measurements as soon as the floods arrive. The engineer travels all over the massif, measures any floods he encounters, takes note of any traces of flooding, estimates floodwater discharges, and records any changes in spring outlets, etc. At the end of the season the result is a complete study of the run-off in the experimental basin, a complete diagram of the flood or floods running into the main wadi, and a fairly good knowledge of the whole of the precipitation and run-off in the massif. This method has been used successfully in the southern Sahara since 1957. The information recorded at one of these stations was published in the 1957 edition of the *Annuaire Hydrologique de la France d'Outre-Mer*. The results of such research seem to warrant more sustained efforts in this direction.

The establishment of three or four permanent stations in the most suitable regions of the Sahara would also seem to be warranted. It would then be possible to record variations in the hydrological régime over much longer periods.

If we except the Niger, which hardly touches the Sahara, the only river which crosses the desert is the Nile, on the banks of which all the life of Egypt is concentrated. The Nile occupies a situation completely apart from other river systems in African hydrology: its lower valley at least is as well known as those of the great European rivers. In the first place, records of river levels which go as far back as thirteen centuries ago are provided by the Nilometers. Secondly, since the late nineteenth century and more particularly since the early years of the twentieth century, a great deal has been done to establish a system of gauging stations along the course of the river. The result is that the main station at Aswan now holds a series of exact and reliable records from 1869 onwards, which compares much more than favourably with the situation in the whole of tropical and equatorial Africa where the networks of gauging stations are of much more recent date.

We should be careful to appreciate the records provided by the Nilometers at their proper value. A number of authors have shown that for various reasons these records cannot be considered absolutely reliable. They point out, for example, that the levels of the river bed may have changed, that the Nilometers themselves have probably been changed, that the original records may not always have been available for reference, that the recording practices are subject to varying individual interpretations, that the conventional figures recorded may not always represent the actual levels reached, etc. Despite these objections, however, the qualitative data they offer are of real value. In particular they show that the extreme levels of the highest and the lowest floods which occurred prior to the nineteenth century did not differ appreciably from the extreme levels recorded since 1869.

The information gained from this ancient system therefore provides a valuable background to the long series of observations made at Aswan. The Nile network is thus practically the only hydrometric system in Africa which is not subject to the great disadvantage of having to work with records that are of only very recent date. We shall make further reference to the Nile later when we come to discuss the tropical and equatorial zones.

Hydrogeological studies are obviously of the greatest importance in the desert zone and such studies have been carried out in considerable detail in the relatively well-populated northern region.

In the north a great deal of research, much of which has produced spectacular results, has been done on the great Intercalary Continental water-bearing formations, the Miopliocene aquifers of the Wadi Rhir, the Tunisian shotts, and the underground waters of the coastal region of the great Syrte. Nevertheless, much study remains to be done, not only in the way of understanding the characteristics of these aquifers and the direction of the flow but also with the object of gaining a general idea of the water balance. The main object of hydrogeological research should be first to discover new resources and secondly to determine to what extent the known underground waters can be exploited. In Egypt lengthy investigations have been made of the Nubian sandstone and, further north, of the underground waters of the delta, but it seems that no substantial increase in the underground resources of these regions can really be hoped for.

Though less detailed research has been done in the centre of the Sahara than on the northern edge, these central areas certainly offer interesting possibilities; such possibilities, however, will only be discovered and developed extremely slowly in view of the vast expanse to be covered.

Further south the same formations as are typically found in the northern regions reappear: among them are the characteristic forms of the Intercalary Continental, the Nubian sandstones, and other sedimentary formations such as the recent alluvia of the Chad Basin. A good deal of exploratory work is being done with the object of establishing watering places for cattle, and considerable progress has been made in the search for underground water, but here, even more than in the northern Sahara, there is still a very long way to go.

Erosion is most marked in the mountain massifs but this phenomenon can only be studied in relation to run-off and detailed observations of run-off are very hard to come by. Analyses of the chemical composition of the water are essential and these must be carried out at the same time as hydrogeological research.

Another phenomenon of which very little is known is evaporation; the information obtained from Piché apparatus is not readily usable, and pan observations are only infrequently carried out. There are four main problems to be solved. These are: (a) to measure evaporation losses from pans under normal conditions; (b) to correlate the information obtained from the pans with the evaporation losses from large bodies of water;[1] (c) to determine the variations in evaporation which occur in certain microclimatic conditions (e.g., at the head of a gorge or in 'gueltas'); (d) to investigate evaporation from the ground where there is underground water at a very shallow depth. Research on all these subjects can be done but the work will be long and very expensive.

TROPICAL SAHELIAN REGIONS

The limits of these regions are not easy to define. We may take them as extending from the 200 mm. isohyet, in the north, to the 700 mm. isohyet west of Lake Chad, and the 800 mm. isohyet from Lake Chad to Ethiopia in the south. This southern limit runs from Dakar,

1. Some initial information which may help to solve this problem has been obtained from a study of the water balance of Lake Chad, situated near the southern boundary of this zone.

then to Segou and to Niamey and south of Lake Chad whence it crosses the inland delta of the White Nile and ends on the Red Sea coast south of Massawa; this curve towards the north is to account for the climatic changes brought about by the Ethiopian highlands.

Except in the Sudan, the number of rain gauge stations per unit of area is low. There is one station for every 6,000 sq.km. in former French West Africa, one for every 10,000 sq.km. in the Chad region and one for every 3,000 sq.km. in the Sudan. However, this density is much greater than that found in the desert and the information obtained from it is sufficient to provide the main outlines of the isohyet network for the plains where variations in annual rainfall are progressive. But when we come to the mountain areas of Cameroon, Wadai, Massalit and Ethiopia, such a network is far too scattered.

In many places observations have been taken only over a very short period. For example, in former French West Africa, a maximum of thirty-five years, but more often twenty-five years; in the Chad area, twenty-five years maximum, but usually ten to twelve years. In the Sudan, however, the oldest stations have been operating for sixty years and many others for forty years.

Generally speaking, the number of recording rain gauges from which rainfall intensity figures can be obtained is quite inadequate.

Research on run-off should be carried out on four different types of terrain:

1. The great rivers coming from the south—the Senegal, Niger, Shari and the Nile—to which we shall refer again later.
2. The branching systems and flood plains of these great rivers.
3. The watercourses originating in the Sahelian zone.
4. The experimental basins.

Nearly all the great rivers flowing into these regions are subject to degradation marked by: the extension of the flood plains and the formation of distributaries; marked reduction in the amount of water flowing from the south; and the self-regulation of flood discharges. What is required is a clear definition of the hydrographic system and an investigation of the way in which flood discharges are exchanged throughout the various parts of the system. Progress in research in this field varies widely. Fairly complete surveys have been carried out on the Logone and the Nile, others have been begun on the inland delta of the Niger but very little has been done on the Shari and the Senegal. Surveys of this type are lengthy and involve considerable expense and difficulty.

The number of rivers which rise in this zone is small except in the extreme south. On these rivers, between the Atlantic Ocean and Dar-Fur, there are some twenty stations most of which are calibrated.[1] At the oldest of these stations, on the Chad, observations have been carried out for six years. Very little is known of the flood plains and the distributaries of these rivers. In addition many other hydrographic systems which are too degraded to give rise to watercourses recognizable as such have not been surveyed at all.

And yet this is a zone where surface water is sometimes abundant during the rainy season and where water development schemes for agriculture would be worth while if the population were more numerous and, particularly, if the long distances to the coast did not inhibit production so seriously.

While it would be premature, generally speaking, to envisage actual surveys and hydraulic development plans for these regions, the time has come when systematic basic studies must be regarded as a necessity. An increase in the number of gauging stations would perhaps not be advisable in view of the financial outlay entailed. It would be sufficient to maintain about thirty stations in permanent working condition and to undertake, for periods of three or four years, studies of individual river systems, beginning with those regions where further development seems most urgently called for.

So far, ten experimental catchment basins have been surveyed in the Sahelian regions of former French West Africa and the Chad. An initial outline of the run-off characteristics of the most common types of soil has been provided by these surveys and the results obtained can be applied to a number of basins in Nigeria and the Sudan. These surveys must be supplemented by investigations of other soil types and slopes; what is more important is that they should be followed up by observations of basins intermediate in size between the small experimental basins and the basins of the larger rivers referred to above.

Hydrogeological studies are not as important here as in the Sahara since surface water is more abundant and in any case there are many places where crystalline outcrops seem to show that the prospects of finding underground water reserves are not encouraging. There are, however, cases when detailed hydrogeological surveys are necessary, for instance, for the provision of fresh water supplies for large towns such as Dakar and the establishment of water points in certain valuable grazing areas which would otherwise remain unexploited. For this reason prospecting for underground water has been carried out at many places throughout the whole Sahelian zone. Good results have been obtained in the Ferlo desert (Senegal), Mauritania, Niger, the recent sediments of the Chad basin and, in particular, Nigeria where an ambitious scheme has been put into effect in recent years. But despite these interesting cases it can be said that the artesian phenomena which occur so frequently in North Africa are much less apparent in the Sahel.

In some places soil erosion is almost as severe as in North Africa. So far little research has been done on this subject, but it could well be combined with work on the experimental basins.

The data obtained from observations of evaporation from Colorado pans are sufficient to establish orders of

1. Stations on rivers which flow from the Ethiopian highlands are not included in this total.

magnitude for evaporation throughout the zone. As a result of the Lake Chad surveys these pan evaporations can be used to determine the evaporation losses from large expanses of open water. Nevertheless, further studies are necessary, particularly on waters which are encumbered with vegetation and on damp soils—a branch of investigation on which very little work was done until recently in this zone.

TROPICAL REGIONS IN THE NORTHERN HEMISPHERE

The transition from the tropical régime to the equatorial régime is so gradual that it is very difficult to state exactly where the southern line of demarcation should be drawn. Roughly it could be said to run from Freetown through the centre of the Ivory Coast, slightly to the north of the Dahomey coast, north of Yaoundé, south of Bangui, to cross the Nile south of Mongalla; thence it would curve south to skirt the Ethiopian highlands and finally strike the Somali coast where, under the extremely arid conditions which prevail, any attempt to distinguish the tropical régime and the equatorial régime would be artificial.

Rain gauge stations are far less widely scattered here than in the Sahelian region. The densities are one for every 1,000 sq.km. in Nigeria, one for every 3,500 sq.km. in former French West Africa, one for every 2,000 sq.km. in Ghana, one for every 4,200 sq.km. in Chad and North Cameroon, and one for every 7,000 sq.km. in the Sudan.

The density of the network in the Chad area is far below what is required, and even more so in Ethiopia. In both these territories attempts to improve the situation would be fraught with very grave difficulties.

The oldest rain gauging stations date from 1920 in former French West Africa, from 1934 in the Chad area, from 1926 in Ubangi, from 1900 in Ghana, from 1900 in the Sudan and from 1898 in Ethiopia. Generally speaking it can be said that the networks in former French West Africa and Ghana were set up between 1922 and 1930, those in the Niger Republic and Cameroon in 1940, those in the Chad area and Ubangi in 1950 and that in Sudan in 1914.

The periods over which observations have been made are in many cases too short to provide any useful additional information to that obtained from the river gauges.

Though there are more stations per unit of area at which rainfall intensities are measured in this zone than in that discussed earlier, the number of such stations still needs to be increased. A number of important rivers, most of which are permanent, rise in this zone including the Senegal, Niger, Benue, Volta, Sanaga, Shari, Ubangi and the main branches of the Nile.[1]

The number of well-calibrated stations per unit of area varies in general from one for every 10,000 sq.km. to one for every 25,000 sq.km. It may be higher in certain catchment basins which have been studied in more detail, such as the Konkouré where there is one station for every 2,000 sq.km. but it is lower elsewhere for example in the basins of the Volta and the Benue, and even lower still in the upper basins of the Blue Nile, the Atbara and the Webi Shebeli.

When the terrain of the basins is not too broken a density of one station for every 10,000 sq.km. is approximately enough to provide a general outline of the hydrology of the great basins in this zone where the climate is homogeneous, but such a density is insufficient in mountainous areas. No real understanding of the hydrological régime of a basin in slightly hilly country can be obtained with a density of only one station for every 20,000 sq.km. For this reason, a considerable effort is needed to set up new gauging stations in the less well-equipped basins.

Only in the Nile basin do the periods of observation go back for a relatively long time. Though the oldest station in the tropical zone dates from 1900, more than half of the stations have carried out observations since at least 1908. A few new stations have been established since 1935. This total collection of records, supplemented by the records from Aswan, covers very dry periods (e.g. 1913) and very wet periods. Its coverage is sufficient to allow an exact calculation of averages to be made.

In the other tropical basins the situation is much less favourable. The major part of the networks in these basins was installed in 1950 (Senegal), 1949 (Niger), 1950 (Upper Benue), 1947 (Sanaga), 1951 (Shari) and 1952 (Ubangi). However, there are two circumstances which do much to mitigate this disadvantage:

1. The hydraulic variations recorded are comparable over vast territories so that if in a catchment basin of 300,000 sq.km. for example, thirty stations show readings for fifteen to twenty years and one main station has observations for fifty to sixty years, this last station could provide information which would allow perfectly valid corrections to be made.
2. The majority of the tropical waterways have been used for navigation and in many cases, as soon as the operating companies were established, river gauges were installed and careful readings were taken. Thus there is at least one reference station for each basin, for example: Kayes (1892) on the Senegal, Koulikoro (1908) on the Niger, Makurdi (1922) and Garoua (1930) on the Benue, Fort-Lamy (1933) on the Shari[2] and Bangui (1911) on the Ubangi. In addition, other observations from gauging stations, which though founded more recently have records for at least twenty years, and some isolated data also contribute useful information.

Finally, apart from the Benue and the Sanaga there is a certain correlation between the neighbouring tropical basins; thus certain qualitative inferences can be drawn from variations in the nearest large river within the

1. The only equatorial branch of the Nile, the Bar el Jebel, though a main tributary, contributes only to a minor degree to the total volume of the Nile flood.
2. Supplemented by observations carried out on Lake Chad.

general context provided by the variations in the flow of the Nile at Aswan.

The situation is therefore less serious than it might appear at first sight but careful attention to the continuity and quality of the observations of the existing network is still required. On the other hand correlation studies of the hydraulic variations of the neighbouring rivers must be carried further wherever observations have been carried out for a sufficient length of time.

The experimental basins are fairly numerous: eight in former French West Africa, five in Cameroon, two in Chad and the Central African Republic. Here as in the Sahel these basins are sufficient in number to allow calculations of run-off characteristics in certain of the more common cases to be made, but this network still needs to be enlarged. There is still a need for more thorough infiltration studies to be carried out in the existing basins.

The absence of information concerning basins of between 100 and 3,000 sq.km. in area constitutes a most serious gap in our knowledge in this field. Systematic observations of such basins would allow us to link up the results obtained in the experimental basins, which are valid up to 100 sq.km., with those obtained by gauging stations in the great river basins.

Discharge rates recorded at the main stations in former French West African territories, the Chad Republic and the Central African Republic are published regularly in the *Annuaire Hydrologique de la Communauté*. Discharge rates in the Nile basin are also published regularly.

Surface run-off is practically a sufficient source of water supply in these regions. The geological structure of the terrain, which is either crystalline or markedly metamorphic, is hardly compatible with the existence of large underground water reserves. However, despite these unfavourable conditions the need for regular water supplies for towns and villages all the year round in both the English-speaking and French-speaking territories has made it necessary to put down a large number of bores.

In the centre of this zone the Benue sandstones have been successfully explored and the sedimentary layer which extends well into the Sahelian regions has been satisfactorily plotted. At the eastern extremity of this zone the sedimentary formations of Somalia have been drawn on very heavily to supply the needs of grazing animals since practically no surface water is available in the area. A fair number of surveys has been carried out for strictly local needs, such as water supplies for small settlements, on the recent alluvia of the flood-plains of the watercourses and at the base of laterite formations where water is often found.

Little erosion takes place on land with natural plant cover (except of course in Somalia); cultivated lands are much more heavily eroded. As the cultivated area is not very extensive in most of the large basins the quantity of material transported in the great rivers is small so that measurements of material in suspension are almost enough to provide a basis for the study of the transportation of solid material. A few series of observations of this kind have already been made and it would be of value to extend this survey to other basins. Similarly, measurements of erosion on experimental plots should be carried out more frequently and systematic studies should be made of the influence of the slope and the amount of annual rainfall.

As a rule the waters in this zone are soft, but few measurements of water quality have been made.

Measurements of evaporation on Colorado pans are fairly frequently carried out either for the purpose of studying evaporation losses for large dam construction projects such as those on the Volta, Konkouré, etc., or as part of observation programmes in experimental basins. Nevertheless a few studies of the water balance of expanses of water under favourable conditions would help a great deal in determining the value of the coefficient which would relate evaporation from pans to evaporation from large water surfaces. Similarly theoretical studies of potential evapo-transpiration are required.

EQUATORIAL REGIONS

These regions extend between the northern limit indicated above and a southern limit which is equally imprecise and might be represented by the eighth or ninth south parallel. In West Africa there are few large watercourses; but in Central Africa, from west to east, there are the Ogowe, the main part of the Congo Basin, the region of the Great Lakes and the headwaters of the Nile. The eastern coast, which is badly watered, has many areas which are semi-arid or even arid in places.

The density of the rain gauge network varies greatly; it is extremely low in Liberia, almost adequate on the coast of West Africa, but between the Cameroon Republic and the Indian Ocean it is far below what is required except in a few privileged areas. There is a relation between this variation and the low population density and the high illiteracy rate.

What is even more serious is that in many cases observations have been carried out for only a very short period. The majority of the stations in the Republics of the Ivory Coast and Dahomey date from 1923 and in southern Ghana and southern Nigeria from 1930; in the Republics of Gabon and the Congo the majority of the records available are utilizable only from 1949 onwards; in Uganda and Kenya from about 1935 onwards and in Tanganyika from about 1935 onwards.

In the former Belgian Congo the situation is a little more favourable. About one-fifth of the stations were established before 1930; the network was improved in 1940 particularly in the '*graben*' region where the heterogeneous character of the rainfall distribution requires a very dense network.

Observation periods in the basin of the Ogowe and southern Cameroon are so short that the available data are of very little help in studies of annual average flows and particularly of variations from one year to another.

Detailed precipitation studies have been carried out in the former Belgian Congo and in Kenya, but in these regions as in the tropical zone the number of intensity recorders needs to be increased.

In most of the equatorial regions the information obtained from the network of gauging stations is less complete than in the tropical regions either because the stations are too few or because the observation periods are too short. The Ivory Coast Republic has a relatively dense network of one well-calibrated station for every 10,000 sq.km., but the oldest of these stations dates back only to 1949.

The equatorial network of the Cameroon Republic is a little less dense. There is one station for every 11-12,000 sq.km. and the oldest observations also go back to 1949.

In the Gabon Republic, in the catchment basin of the Ogowe, where travelling conditions are extremely difficult there is a density of only one station for every 28,000 sq. km., which is quite inadequate. On the other hand, this network includes the only old-established equatorial station west of the Congo—at Lambaréné on the Ogowe, where readings have been taken for some twenty-five years.

The Congo Republic, which covers the basins of the tributaries on the right bank of the Congo (Ubangi) and of the Kuilu, has an average of one well-calibrated station for every 7,000 sq.km.; this average is largely accounted for by the number of stations in the Kuilu-Niari basin, where under the same conditions there is one station for every 3,000 sq.km. but where the oldest station dates back only to 1948.

The territory of the former Belgian Congo which corresponds to the greater part of the Congo basin, will have a very good hydrometric network when the majority of the present water level stations has been calibrated. It should be possible to transform about 250 of these into gauging stations, which would give a density of one station for every 9,000 sq.km., fairly evenly distributed. Observations have been carried out for fairly long periods; for sixty years at two stations, for fifty years at nine stations and for more than forty years at twenty-nine stations.

The system was completed in 1958. Unfortunately the equipment of less than fifty stations can be considered as having been calibrated provisionally.

The same difficulties are encountered in Kenya and in Tanganyika, but with one slight difference; here there are extremely wide differences in the depth of precipitation. The number of stations per unit of area varies considerably. Tanganyika can be considered to have an average density of one gauging station for less than 3,000 sq.km. and in some areas where special studies have been carried out[1] the density is higher than one station for every 2,000 sq.km. In the semi-arid areas, however, the density is much lower. In general, observation periods are very short since this territory had only two gauging stations in 1947 and the majority of the network dates only from 1954. A great effort is now being made to calibrate these stations.

In Kenya the average density is higher and the observation periods are longer; one station on the Tana has readings dating back for thirty-seven years, several other stations for more than twenty years and even more for ten years.

Fortunately, levels in some of the Great Lakes have been recorded for a considerable time and these records provide good reference points. For example observations have been carried out on Lake Victoria since 1889 and on Lake Albert since 1912.

Here we should note that the Uganda network has two particular characteristics which distinguish it from other networks: (a) it has been established for some time, some of the larger stations having records which go back for about fifty years, and has a fairly high density of one station for every 2,000 sq.km.; (b) since the hydrographic system in the area is a complex one, it is not easy to calibrate many of the stations.

In the western part of this equatorial zone the lack of old-established observations is a great obstacle to hydrological surveys, particularly since some of the rainfall data also refer only to quite recent periods. An attempt has been made to overcome this serious disadvantage by increasing the number of experimental basins of 10-50 sq.km. in area; nine such basins have been established in the Ivory Coast, one in Dahomey and eight in the Congo (Brazzaville). The main object of establishing these basins is to investigate floods.

A number of experimental basins of slightly larger area have just been set up in Ruanda-Urundi.

Investigations have also recently been carried out in some very small experimental basins in Kenya, Tanganyika and Uganda, the main purpose of these investigations being to determine the influence of plant cover on run-off. In some of these areas, particularly in Tanganyika, an attempt has been made to discover the direct relation between run-off and rainfall in order to work out long-term discharge patterns. These co-ordinated studies have produced some quite remarkable results.

West of the Congo discharge figures for catchment basins of less than 100 sq.km. can usually be estimated. On the east side such estimates are much more difficult to make. In all parts of the equatorial zone, as in the tropical zone, difficult problems are encountered in the study of catchment basins of 100 to 3,000 sq.km. in area.

Discharge figures for the main stations in the Republics of the Ivory Coast, Cameroon, Gabon and Congo (Brazzaville) are published annually in hydrological yearbooks. In the former Belgian Congo a yearbook was published giving figures for the majority of the river gauge stations and also some flow data as well.

1. For example, the study of the Rufiji carried out by experts from FAO and the Water Development Department.

Studies of ground-water hydrology have not been carried very far in the territories west of the Congo, since surface water is often abundant and in any case sedimentary formations are rare—although those south of the Ivory Coast and in Togo and Dahomey are being exploited and water supplies for many of the larger ports in this zone come exclusively from underground reserves. Despite the heavy annual rainfall, certain problems connected with providing water supplies are often quite difficult to solve. We could mention some small places in the middle of the forest where an annual rainfall of as much as 1,200 mm. is almost entirely absorbed by the thick plant cover and where the thin alluvial layer over the granite rock cannot provide even the small underground water supply required. However, except in the most arid regions of Togo, Dahomey and certain parts of Ghana, drinking water supply problems are rarely very acute.

The situation is different when we come to the 'graben' region where the annual rainfall is sometimes much lower but where fortunately as a result of volcanic eruptions there are some extremely permeable terrains which often contain excellent aquifers. For this reason hydrogeological studies have been widespread in Ruanda-Urundi, Kenya and Tanganyika.

The permeable terrains of the Karroo in Tanganyika hold considerable resources. But generally speaking there are few really big water-bearing formations in this area like those found in North Africa. The only comparable resources are those on the coastal strip of the Indian Ocean where even artesian water is to be found.

Unfortunately the chemical composition of the water often makes it unsuitable for human consumption or even for irrigation.

Throughout this whole eastern zone a great deal of research is required if only to localize and to establish the main characteristics of the more important underground aquifers, except of course in the neighbourhood of the large cities where the possibilities are well known.

Erosion, which is not significant in forest areas, is much more marked in the savannah regions and in all areas where the forest has been cleared for cultivation.

Little if any measurement of the transportation of solid materials has been carried out in the rivers of the forest region to the west of the Congo. Yet some effort to establish the amount of material transported in simple cases would be useful and would not be difficult to carry out.

On the other hand measurements on experimental plots have been carried out on the Ivory Coast and in the Congo (Brazzaville.) Such measurements should be continued systematically and care should be taken to determine the influence of the slope, of the plant cover and of methods of cultivation.

In Kenya and Tanganyika, where erosion is much more noticeable, measurements of materials in suspension are now being more widely carried out and it is to be hoped that even more work of this nature will be carried out in the future. Here we may note that several examples of the measurement of total transportation in reservoirs have proved most useful, since it has been no easier in Kenya and Tanganyika than elsewhere to develop a convenient method of measuring the bed-load.

Measurements of evaporation in the equatorial zone are not easy to carry out and the task of keeping the pans under close observation is complicated by the rain. Furthermore, as soon as precipitation becomes frequent evaporation drops to 2 or 3 mm. a day thus rendering the task of measurement much more delicate than in the Sahelian or tropical zones.

This is no doubt why only seven Colorado pans (to the best of our knowledge) have been installed west of the Congo. The information supplied by the Piché evaporation meters is very difficult to apply to evaporation from open water surfaces.

What is required in these territories is a map showing pan evaporation figures which could be related at certain well-known points to information provided by the Bellani equipment and to the calculation of the water balance of the large reservoirs. This latter would be a difficult operation since the conditions here are very different from those which obtain on Lake Chad where, except for a few secondary considerations, evaporation losses are equivalent to the discharge of a large river.

Systematic studies of potential evapo-transpiration with Thornthwaite pans and lysimetric tanks would be desirable. The information thus obtained would have to be related to run-off losses in large basins and particularly with the water balances established for the experimental basin.

In the former Belgian Congo an important theoretical and experimental campaign has been carried out on energy balance methods, the use of Bellani equipment and potential evapo-transpiration. Here it would be very desirable if the number of points at which measurements are taken could be increased.

In Kenya, pan observations are extremely widespread; sixty-one pans were in use in 1958 and some have been observed for quite long periods. Considerable attempts have recently been made to ensure standardization of results. These pans are used in association with the Bellani-Cun equipment.

Some calculations of water balances for the Great Lakes have been carried out but for the reasons mentioned above it is very difficult to obtain exact figures for evaporation. In this connexion we should mention certain experiments carried out in the marshes in Uganda. One of the main objects has been to study evaporation losses from water surfaces covered with vegetation. Here as in the Western part of the equatorial zone a survey of sites where conditions are particularly suitable for a study of the hydrological cycle of water surfaces would be of very great value.

SOUTHERN TROPICAL REGIONS

We shall take as the southern border of this zone a line which, though arbitrary, is a convenient one. It follows the southern frontiers of Angola, Southern Rhodesia and Mozambique. This choice of boundary is based on several considerations. In Southern Angola and Northern Rhodesia the annual rainfall decreases as one travels from north to south. Across the southern part of these territories there is a strip running from east to west in which climatic conditions closely resemble those of the tropical Sahelian zone in the Northern hemisphere, mentioned above. This belt, however, does not extend as far as the coast of the Indian Ocean, since from Southern Rhodesia onwards towards the coast the rainfall increases gradually so that the southern part of Mozambique and Southern Rhodesia have hydrological régimes which are distinctly tropical. Bechuanaland and South-West Africa which are at the same latitude, are deserts. Thus our southern limit is drawn in a curve so as to include a group of territories where conditions are clearly tropical. To these we shall add Madagascar.

The average number of rain gauge stations per unit of area is fairly low in Angola, Northern Rhodesia, Mozambique and Madagascar. In addition the distribution of the gauges is extremely irregular and for this reason we give no figures for the average density. In Northern Rhodesia, for example, one could find squares of 10,000 sq.km. in area with a density of one rain gauge for every 250 sq.km.; at the same time there are other surfaces of the same area without a single gauge. There is even one area of 40,000 sq.km. where there are only two rain gauges. Thus any attempt to draw up isohyet charts with complete coverage is difficult; in all these countries, and particularly in the regions away from population centres, the density needs to be improved.

In Southern Rhodesia the coverage is much more regular; in general one can say that there is one rain gauge for every 200 sq.km., which is adequate; but in certain regions to the north and particularly to the east the networks are rather too irregular and need completing.

The periods over which observations have been taken are in general slightly longer than those in the equatorial regions. The oldest stations date back to the period between 1900 and 1910 and there are a fair number of stations which have observations going back for twenty years or so. The networks were completed about ten years ago.

In general there is a fairly low density of gauges which record rainfall intensity and this is a factor which is extremely important to study, particularly in the savannah areas.

The hydrographic system of this region consists essentially of the Zambezi basin with, in addition, several coastal rivers; the Cuanza and the Cunene in Angola, the Rufiji in Tanganyika and the Ruvuma and the Savé in Mozambique. The Limpopo flows along the southern boundary.

Generally speaking, the more arid the basin the more irregular the network of gauging stations—which is more or less normal since the arid regions in this zone are extremely difficult of access in the rainy season and the floods are of extremely short duration.

Here also a distinction should be made between the network of Southern Rhodesia and those of the other territories.

Northern Rhodesia has a little less than a hundred river gauge stations of which probably about thirty only are fairly well calibrated, which corresponds to a density of less than one station for every 13,000 sq.km. Calculated by the same standard the density is slightly lower in Mozambique and much lower in Angola.

It is essential if the future of the hydrological surveys of these regions is to be assured that the existing river gauge stations should be calibrated and that the distribution of stations should be improved.

The observations which have been carried out do not cover very long periods. In Northern Rhodesia the oldest records are those held at Livingstone, which date from 1924, and Senanga, which date from 1932; observations have been kept at two stations since 1948. The network began to develop in 1950 and was considerably extended in 1957. The situation is no more favourable in Mozambique and in Angola. The detailed studies which have been carried out at Lake Nyasa are a valuable source of reference, since continuous observations have been taken since 1916 and there are even data available from as far back as 1896; this hydrographic information, however, cannot be applied to the main tributaries of the Zambezi which are situated much further towards the east. For statistical purposes these observation periods are very short.

In Madagascar the network density is scarcely higher than in Mozambique or Northern Rhodesia; there is only one well-calibrated station for every 19,000 sq.km. although there is a much greater variety of hydrological régimes than in Northern Rhodesia. More calibration of equipment is needed and the distribution of stations should be improved. Here observation periods are very short; the oldest station dates from 1948 and the network was set up between 1951 and 1954. When it is considered that twenty years ago only 20 per cent of the rain gauge stations had been set up it can be seen that any exact estimate of average over long periods is very difficult to obtain.

In Southern Rhodesia the situation is much better in many respects; here of course the country is much more developed economically and conditions for hydrological surveys are somewhat less difficult.

The stations of the network are distributed as uniformly as possible and about sixty of the total of one hundred and twenty-odd river gauge stations are calibrated; this gives a density of about one calibrated station for every 6,000 sq.km., which is quite a reasonable density for tropical Africa. Great progress has been made with the provision of level recording equipment for these stations and this is the first network of this kind to be encountered since leaving North Africa. Unfortunately the periods over which observations have been made are short. One station dates from 1924, one from 1925, one from 1927, one from 1928, a few from 1947-48 and 1949 and it was not until 1950 that a large number of stations were set up. Here as in Algeria an attempt has been made to compensate for this lack of information by correlating run-off and precipitation data; in particular graphs have been established for the various soil types and isohyet charts have been drawn up.

Research work has been carried out in experimental basins in four places in Southern Rhodesia. The main purpose of this research was to determine the influence of changes in plant cover on run-off characteristics. Observations carried out on experimental plots have been combined with these studies.

In Northern Rhodesia detailed hydrometeorological investigations have been carried out in certain basins with the object of establishing the relationship between run-off and precipitation.

In Madagascar work has been done on only one experimental basin, but two other such basins are now being set up.

It would be advisable to extend research work of this kind to cover the whole of this climatic zone.

For Madagascar, discharge figures recorded at the main stations are published in the *Annuaire de la Communauté*. A hydrological yearbook is also published in Southern Rhodesia and the first discharge figures for Northern Rhodesia have just been published.

Investigations concerning the transportation of solid materials in watercourses are well advanced in Southern Rhodesia where erosion is considerable, and systematic samplings of material in suspension have been made at a large number of gauging stations. The equipment used has been standardized and investigations are now being carried out in order to set up stations where the transportation of materials in suspension can be observed continuously.

In Madagascar a few studies have been made of silt discharge but a great deal more work needs to be done on this subject. The same applies to observations of erosion on small plots.

We shall leave aside for the moment the question of underground water research since in the semi-arid regions, where particular progress has been made in this field, the situation closely resembles that which will be described below in connexion with the southern desert zone.

In Southern Rhodesia there is a good evaporation pan network and the equipment has been standardized. The relations between the different kinds of pans in use are also being studied.

A special study is being made of evapo-transpiration on experimental plots and lysimeters. An attempt is also being made to determine by this means the water consumption of the different types of plant cover.

In Southern Rhodesia, Nyasaland and Madagascar, much less progress has been made in field studies. Some lysimetric studies have, however, been made in Madagascar. These need to be carried further in order to obtain fuller and more accurate information for the potential evapo-transpiration charts which have hitherto been drawn up on a theoretical basis.

THE SOUTHERN DESERT ZONE

This zone consists essentially of the territories of South West Africa and Bechuanaland, which on the whole are slightly less arid than the Sahara.

Here again we encounter characteristics which closely resemble those noted in hydrological studies of the Sahara. The density of rain gauge stations is insufficient and a great deal of importance is attached to hydrological surveys of underground water.

Nevertheless the establishment of reservoirs in the sandy alluvia of watercourses in South-West Africa has made it possible to develop hydrological studies of surface water to a far greater extent than in the Sahara; for example flow volumes for certain watercourses can be worked out for periods of over twenty years in some cases.

This particular method of storing the discharge of watercourses has made it possible to build up an extremely valuable body of information concerning the transportation of solid materials.

The underground water resources vary w dely and the potentialities are nowhere near as great as in the Intercalary Continental of the Sahara. A few large springs and a few artesian reservoirs are to be found in the dolomitic areas of South-West Africa. Use is also made of recent alluvia of temporary watercourses. These underground reserves have been drawn on considerably, since they constitute the main source of water supply for the country. Systematic studies have been made of wells and borings and as a result a fair amount of knowledge has been obtained of underground reservoirs. As on the northern fringe of the Sahara there is a risk of over-exploitation and for this reason it is important that the means by which these reservoirs are charged and the possibilities of carrying out artificial replenishment should be investigated thoroughly.

In Bechuanaland, underground water resources are less plentiful and less hydrological research seems to have been done on this subject.

Examinations of the quality of the water are carried out systematically; such examinations being necessary in these regions, where the water is often unsuitable for consumption without treatment or may even be too salty to be used at all.

A little more research on evaporation has been done in these desert regions than in the Sahara but there is still a great deal to be learned on this subject.

THE REPUBLIC OF SOUTH AFRICA

As we have already seen, the climate here has tropical characteristics in the east and Mediterranean characteristics in the south. The amount of rainfall increases as one travels from west to east. Wide variations in precipitation are noted in the mountainous areas along the east coast and a large part of the territory in the centre and the west is arid or semi-arid.

Generally speaking hydrological research here can no longer be strictly compared with research in an underdeveloped country. Because of the degree of economic development, the problems found and the type of research carried out are the same as in Europe and in the United States.

The amount and distribution of the rainfall are well known. The average density of gauging stations is about one for every 300 sq.km. and much higher in the whole zone where the annual amount is more than 300 mm. Observation records are available for long periods; two rain gauges have been observed for a hundred years and two first-class gauges for sixty to eighty years. On an average the gauging stations have been in operation for between twenty-five and forty years. There are about a hundred self-recording gauges, some of which have records going back twenty years. A considerable body of information is thus available to hydrologists.

The hydrographic network covers the catchment basin on the right bank of the Limpopo, the drainage basins of the Orange and its tributary the Vaal and of numerous small coastal rivers.

There are about 320 gauging stations including 270 which can be considered to be well calibrated. The average density is about one station for every 4,000 sq.km. but half the territory has practically no hydrographic network at all so that in the eastern and southern regions the density can be said to be about one station for every 2,000 sq.km., which is quite acceptable. Observations have been carried out for relatively long periods and twenty stations have been in operation for fifty-five years. The information thus available, which tropical hydrologists would probably find satisfactory, is only just enough for a territory where conditions vary widely from year to year and where there are marked differences in the amounts of precipitation from one basin to another.

Studies are being carried out in a number of small experimental basins with the object of determining the annual volume of water available to supply the underground aquifers. Detailed investigations have also been made to determine the type of plant cover which provides the best infiltration conditions.

Erosion is widespread and systematic studies have been made of the transportation of materials in suspension at eighty stations. The network also includes a number of experimental basins and erosion study plots.

Underground water resources are drawn upon heavily to provide supplies for isolated farms and population centres and for irrigation but such resources are not very abundant. In the dolomitic calcareous formations a certain number of springs, some of which produce considerable volumes of water, are to be found. There are also a fair number of thermal springs.

Artesian water is rare. Most of the wells have been bored in the superficial parts of crystalline rocks which have been weathered or fractured, in the dolomitic terrains traversed by dykes and in the hard formations of the Karroo. The results of tens of thousands of borings are being studied systematically by hydrogeologists. Geophysical methods have been adapted to suit the particular conditions of the country. Aerial photography is widely used in prospecting. An attempt is being made to correlate the results obtained from experimental basins with those obtained from borings and it has even been possible to form veritable experimental basins underground owing to the damming effect of the 'dykes' which traverse the dolomitic terrain. Water requirements are considerable and the intensive use of underground resources makes a detailed study of ground water recharge absolutely necessary.

Studies of the composition and quality of water are carried out systematically.

For the study of evaporation an extensive network of evaporation pans has been established; this consists of 150 stations equipped with Symons pans which are being gradually replaced by U.S. Weather Bureau Class A pans, about seventy of which are in operation at the moment.

CONCLUSIONS

We have not been able in the space of this chapter to mention all the studies of interest that have been carried out in the various parts of Africa or to list in detail the work that still remains to be undertaken in the various branches of hydrology in each territory. This would have required consultations with the leading climatologists, hydrologists, hydrogeologists and agronomists of the various territories and even quite lengthy visits to certain regions of Africa with which we were not acquainted. The short time at our disposal made such investigations impossible.

There are, no doubt, many points which have escaped us; particularly, perhaps we were not aware of some recent investigations, since in many cases we consulted documents going back many years without being able to contact the hydrologists of the countries concerned.

On the other hand we deliberately took little account of theoretical studies and turned our attention more particularly to the investigation of the whole body of observation and measurement data available in the various countries. It can be said that the great disadvantage under which practically the whole of Africa labours is the sparsity of observation data and the fact that records cover only short periods of time. It is to these matters that hydrogeologists must turn their attention. The most subtle reasoning cannot compensate for the absence of adequate information. How often are African hydrologists obliged to work out mean annual discharge figures, an exceptional flood discharge or the evaporation losses from a body of water, with only insufficient data to go on, and how often must a conscientious statistician hide his face in horror at the audacity of the methods to which he must have recourse? But answers must be given to the barrage builder, to the agricultural engineer, to the bridge builder, who cannot afford to wait ten years until the series of observations has assumed reliable proportions.

Every attempt must therefore be made in surface hydrology to complete those basic networks which are insufficient, to calibrate them, and above all to ensure the continuity of observations—and this in Africa is no passive operation. Recording gauges must be inspected every two or three months, river gauges knocked over by boats must be put back into position, water level recorders must be repaired; in addition, hydrologists are called upon to carry out inspection trips to check the gauges and measure extreme discharges, a feat which sometimes calls for considerable athletic prowess—all this regardless of such things as sickness, staff vacancies, unexpected shortages of funds and even political upheavals.

Experience has shown that the only way to ensure the coverage required is to establish *local hydrological services engaged exclusively in hydrological investigation and research.* Temporary missions of specialists may contribute very effectively to the establishment of such services, but the greatest contribution they can make is with respect to the specialized studies needed for various development projects. After the departure of the mission the data collected can then be correlated with those of one or two stations of the basic network and fully exploited.

Research on experimental basins is of particular value in African countries. It can compensate for the lack of old-established observations and enable the processes of run-off to be more thoroughly understood. Such research should be complemented by detailed precipitation studies, which are also needed for erosion surveys.

In studies of evaporation an effort should be made to standardize methods and instruments. Such standardization should not, however, be carried too far. No equipment at present available can give complete satisfaction between the 20 mm. and 4,000 mm. isohyets. Particularly where evaporation is concerned, a certain number of stations are needed where coefficients can be worked out to correct information obtained, for the various types of climate, from standard equipment and that obtained from the older types of equipment. An effort must be made to locate lakes and stretches of water on which to calculate evaporation losses as accurately as possible in relation to the hydrological cycle. Since exceptional conditions are required, there are few bodies of water from which accurate estimates can be made. Observations of evaporation from shallow underground water tables and of evapo-transpiration must be carried out much more extensively, wherever possible in connexion with studies of the water balances of experimental basins and the calculation of run-off losses in large basins.

With regard to the measurement of the transportation of solid materials, more frequent measurements of reservoir sedimentation and of experimental pits are needed since these are the only means of determining the extent of scouring and transportation. Another essential is the standardization and extension of measurements taken on experimental plots but here again, several types of standard plots are required. The installation of continuous measuring stations such as those used in Southern Rhodesia should be extended to many parts of Africa.

In *underground hydrology the continuous nature of* the measurements and the length of the periods of observation are often less important than in the study of surface run-off, but the work to be accomplished in certain territories is still considerable and will require a great deal of time. Here the basic work is of paramount importance—in geology, cartography and surveying—and quantitative factors should not be neglected, particularly with regard to the replenishment of aquifers, whatever difficulties this may appear to involve.

The co-ordination of investigations in certain large basins and, above all, the systematic exchange of results and working methods among the different territories appear to us indispensable.

All this will be very costly, particularly in view of the fact that the natural difficulties peculiar to the greater part of the African continent call for far higher expenditure for the same amount of work than would be needed in Europe or in the United States of America. One may then ask whether the expenditure entailed in such investigations is commensurate with the relatively small amount of economic activity and low population density of certain territories. This is a point of view which could be entertained, and it is true that research can sometimes thus be kept within more reasonable limits. For example, it is for this reason that we admit a density of one station for every 10,000 sq.km. in certain regions. But, at the same time, it is precisely because the greater part of Africa is poor that every effort should be made to improve its productivity; which is why, subject of course to certain conditions, some very costly hydrological research projects can be readily justified. Finally, it should not be forgotten that when economic considerations are being taken into account hydrological information may be used as much as ten or fifteen years after it is recorded; this presupposes a policy of long-term research work which is not limited to a few areas of interest for the immediate future.

Bibliography

The bibliography covers publications which deal with the water cycle in Africa, from precipitation to arrival in the sea or in underground aquifers, to the exclusion of those dealing with applied hydraulic engineering. It thus includes works not only on surface hydrology but also on precipitation, evaporation, infiltration and hydrogeology, and publications on erosion with particular reference to solid transports.

In general, the documentation listed here is intended to provide the reader with an over-all view of the hydrological problems of each country, together with the principal characteristics of the forms of precipitation and run-off for the most important natural regions.

References bearing on purely local problems or on highly specialized aspects of certain fields of hydrology, and even those concerned with promising research which has not yet reached the stage of final results, have been excluded. It follows that the choice which has been made does not correspond, in any way, to a classification according to the real value of the publications.

This abridged bibliography should include only works of general interest. Unfortunately these are rather scarce in Africa, and very often it has been necessary to consult a much more complete bibliography—also compiled for Unesco—from which we have extracted certain detailed studies containing material not available in a work of a more general nature.

It is possible that certain publications not giving essential data appear in this listing and, on the other hand, some works containing chapters which would have been extremely useful have been left out. But in Africa, as in many regions in process of development, practical efficiency is more important than perfection and in the time available it was not possible to revise the bibliography more thoroughly.

The reader may find that certain of the references given here have already appeared in climatological, geological and pedological bibliographies; however, these bibliographies have been finalized according to a very strict classification, and there is a risk that certain references which are of essential interest for hydrology, but are perhaps of lesser interest for geology or climatology may have been omitted. For this reason, the present hydrological bibliography has been drawn up in such a way that it constitutes a whole, although this entails some overlapping of the corresponding geological or climatological bibliographies.

All references should, in principle, be later than 1930 but as certain older works are still authoritative, they have been included. Moreover, certain territories have not been the subject of very thorough hydrological studies, with the result that recent documentation is still insufficient, even to give a simple over-all view; in this case too the old references have been retained. Likewise, in the bibliography from which the present work was extracted, the references are not generally later than the end of 1959, but certain publications of essential interest which have been published or circulated since have nevertheless been mentioned.

The documentation on hydrology is somewhat poor. Hydrologists in Africa are overworked and have not always the leisure to prepare printed publications. Hence it frequently happens that absolutely essential data are available only in a very few multigraphed or even typewritten copies, and many documents of this kind have therefore had to be included.

The classification of the references is based on the water cycle, as follows:

I. Precipitation; general climatological data.
II. Evaporation; lysimetric studies; climatological factors affecting these phenomena.
III. Run-off; hydrological balance; rivers, streams and lakes.
IV. Ground water; infiltration; soil moisture.
V. Solid transports.
VI. Composition of water.

The bibliography opens with a special List A on material relating to the whole, or a large part, of the African Continent. List B (starting on page 200) concerns publications of a periodical nature containing climatological or hydrological data such as annals, directories, fortnightly and monthly bulletins, etc.

In List C (page 203), for each of the branches of hydrology indicated above, the entries are grouped by country, as follows: Africa has been divided into climatic belts, roughly meridian, which are considered from north to south. The belts are traversed from west to east. The countries are thus arranged in the following order:

1	Morocco	22	Ghana
2	Rio de Oro; Canary Islands	23	Ivory Coast
3	Algeria	24	Togo
4	Tunisia	25	Dahomey
5	Libya	26	Nigeria
6	United Arab Republic	27	Cameroon
7	Mauritania	28	Central African Republic
8	Senegal	29	Gabon
9	Mali	30	Congo (Brazzaville)
10	Niger	31	Congo (Leopoldville)
11	Upper Volta	32	Uganda
12	Chad	33	Kenya
13	Sudan	34	Tanganyika; Zanzibar
14	Ethiopia	35	Angola
15	French Somaliland	36	Northern and Southern Rhodesia and Nyasaland
16	Somaliland		
17	Somalia	37	Mozambique
18	Gambia; Sierra Leone	38	Republic of South Africa
19	Portuguese Guinea	39	Madagascar
20	Guinea	40	Réunion
21	Liberia	41	Mauritius

Within these divisions items relating to a particular aspect of hydrology, e.g. surface run-off, in each country are arranged in alphabetical order of authors' surnames; when there are several items by the same author, they are given in chronological order. However, certain major exceptions have been made for the sake of convenience, e.g., in the case of maps.

To indicate the nature of publications, the references have been supplemented wherever possible by appropriate symbols suggested by Southern Rhodesia:

Books or bulletins, on sale . . . . (B)
Papers (submitted to a conference), limited number of copies available . . . . (P)

Reports which may be copied . . . . (R)
Journals or periodicals from which extracts can be copied (J)
Maps, on sale. . . . . (M)

It will be advisable to first consult list A, which consists mainly of works of general interest; these will often be sufficient for the user of the present bibliography.

The following sources were used in compiling the bibliography:

The bibliographical lists supplied by the local hydrology correspondents of the Commission for Technical Co-operation in Africa South of the Sahara, who in this case were themselves responsible for the selection of items. Unfortunately some new States have not yet appointed correspondents;

The lists supplied by the climatologists, hydrologists, hydrogeologists and hydrological research offices of the various African countries, and by European experts who have studied the hydrology of those countries:

Documentation which the writer has been able to consult on the spot; documentation kindly made available by the French Direction Météorologique Nationale; the writer's own documentation which is fairly comprehensive for the territories in the French Community where he is concerned with almost all the work on surface hydrology;

Bibliographies, not very numerous, among which the following may be mentioned: (a) the extremely full *Bibliography of Regional Meteorological Literature*, Vol. I, *Southern Africa*, by R. J. Wenter; (b) the important bibliography attached to Friedrich Wilhelm Lockerman's thesis, *Zur Flusshydrologie der Tropen und Monsunasiens*; (c) the *List of Publications of the Nile Control Department*; (d) the bibliographical lists attached to the articles by G. Drouhin, Y. M. Simaika and H. F. Frommurze in *Hydrology of the Arid Zone*, published by Unesco.

Lastly, a large number of shorter bibliographical lists attached to a variety of works have yielded useful additional information.

From the foregoing it will be apparent that the writer has received a great deal of assistance in the compilation of the present bibliography, and he would like to express his warmest thanks to all who have thus helped him with documentation or advice.

A. PUBLICATIONS RELATING TO ALL, OR LARGE AREAS, OF AFRICA

I

(Precipitation; general climatological data)

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(Evaporation; lysimetric studies; climatological factors affecting these phenomena)

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III

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   Les fascicules parus au 1er septembre 1959 sont les suivants: 1949-50: fascicules I, II, III; 1950-51: fascicules I, II, III; 1951-52; fascicules I, II, III, IV (*Débits et crues de l'Oued Medjerdah de 1898 à 1952*).
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28. CENTRAL AFRICAN REPUBLIC (See also B.7, no. 4)

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30. CONGO (BRAZZAVILLE) (See A.I, nos. 7, 8, 11, 12; B.30, no. 1; C. I.28, no. 1)

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(Ground water; Infiltration; Soil moisture)

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