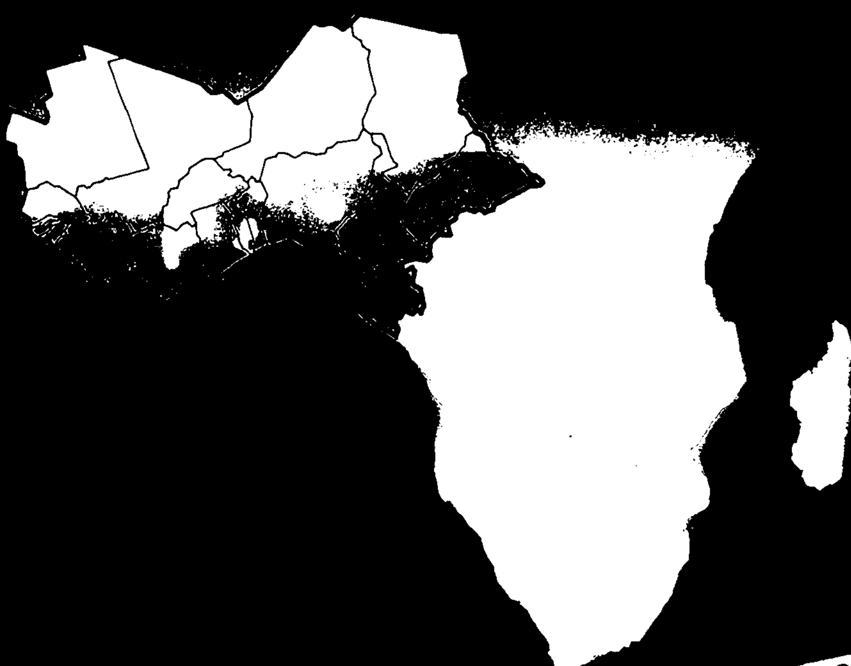
COMMISSION OF THE EUROPEAN COMMUNITIES - CEC

INTER-AFRICAN COMMITTEE FOR HYDRAULIC STUDIES - ICHS

EXPLANATORY NOTICE AND RECOMMENDED USAGE OF THE MAP OF POTENTIAL GROUNDWATER RESOURCES IN WESTERN AND CENTRAL AFRICA

1/5,000,000

MAPPING PROGRAMME FOR ASSISTANCE IN DEVELOPMENT DECISION-MAKING



BUREAU DE RECHERCHES GEOLOGIQUES ET MINIERES

GEOHYDRAULIQUE

COMMISSION OF THE EUROPEAN COMMUNITIES - CEC

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1:5,000,000-scale

MAPPING OF THE GROUNDWATER RESOURCE POTENTIAL OF WEST AND CENTRAL AFRICA

EXPLANATORY NOTES

MAPPING DESIGNED TO ASSIST IN
DEVELOPMENT DECISION-MAKING

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1:5,000,000-SCALE MAPPING OF THE GROUNDWATER RESOURCE POTENTIAL OF WEST AND CENTRAL AFRICA

Mapping designed to assist in development decision-making

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SUMMARY

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Introduction

AIM OF MAPPING

The knowledge of groundwater resources in Africa has made great strides during the past few years under the impetus of various equipment programmes, in particular those of the **Village Water Supply project.**

The most important aquifers from the point of view of resource potential, in particular those related to sedimentary formations and referred to as **"generalized aquifers"**, are widely tapped for the population's water supply, as well as for farming and industrial ends. A generally satisfactory amount of knowledge of such reservoirs exists, but better definition of their exploitation limits and recharge conditions may be required. Sedimentary formations with such generalized aquifers cover 38% of the area of the 23 states concerned by the present mapping programme ; such aquifers tend to be at depths that require tapping by boreholes.

The greater part of the area mapped (62 %) is, however, made up of crystalline and metamorphic rocks accompanied by sedimentary deposits with highly developed fracturing and fissuring. These **discontinuous-type aquifers** (or aquifers with hydraulic properties resembling a discontinuous environment) only contain local groundwater resources, whether in arid, semi-arid or wet-tropical zones. Moreover, and in contrast to the generalized aquifers, the discontinuous aquifers commonly are shallow or at moderate depth ; exploitation can be both by dug wells and boreholes.

For the past fifteen years or so, notably as part of the International Drinking Water Supply and Sanitation Decade (1981-1990), a large number of rural-area water-supply programmes were carried out and provided new information on fissured and fractured aquifers.

The first experiments on developing these new water resources supplied, from the 1970's onwards, some answers to the basic problem of water availability for a wide variety of needs which faces African countries and development organizations. From that time onwards, planners and decision makers found themselves faced with a generation of new problems which it would be advisable to solve as soon as possible :

- What are **the effective, sure water resources** offered by the discontinuous aquifers in fissured or fractured "hard rocks" ?
- Does the groundwater development of these aquifers enable a guaranteed **drinking water supply** to the rural population, considering the demographic evolution and the increasing per-capita consumption ?

- Over and above the primary satisfaction of domestic needs, can one consider **exploitation of water for other uses,** allowing the development of economic activities (farming, small-scale craft production, pastoral).
- Can the presence of such a groundwater resource contribute to minimizing **the often catastrophic climatic hazards** which have been affecting African countries for around the past years : notably, what "buffer" role can groundwater play in the face of several years of drought and to what extent can the resource be called upon for irrigation purposes ?
- How can one **use the documentary evidence** indispensable for the assessment of new programmes, when such evidence is based on information collecteed by quite disparate means that may not even have a common (scientific) language ?

It was, therefore, important to take stock of the groundwater projects undertaken in the last ten years so as **to create an orientation tool** for development planners based on the use of the West and Central African groundwater resources. The present mapping project was undertaken in the two-fold perspective of (1) **managing** programmes for drinking water supply and (2) **development planning** (especially agricultural). Responsibility for the project was assumed by the Commission of the European Communities (CEC), the prime contractor being the Interafrican Committee for Hydraulic Studies (ICHS), which entrusted the work to BRGM and GEOHYDRAULIQUE.

The 1:5,000,000-scale synthetic map is the embodiment of the combined processing of extremely-varied data : geological, climatological, hydrogeological or purely technical. The aim of this processing was to produce a document couched in an **"economic" language that can be directly understood** by public officials and those in charge of non-specialist financing and development organizations. Moreover, the increasing number of drilling projects, the diversification and eventual change in resource uses led the map-designers to propose a deliberately **evolutive** form of mapping. Computer-assisted mapping has made it possible to achieve this aim, while giving a presentation that is as faithful as possible to the reality of the moment, and which can be revised at any time.

The synthetic map, as an orientation document, can be easily and logically complemented by maps of groundwater potential for each country, at varied scales suitable for the chosen development aims. Any mapping at the scale of a country will contribute to the supply of new information and a resulting gain in data detail and density. Entered into infographic memory, these data will enrich and update by interaction the present map.

Part I

METHODOLOGY

I.1. CONCEPTION OF MAPS OF EXPLOITABLE GROUNDWATER POTENTIAL

I.1.1. General principles

Up to very recently, maps of "groundwater resources" were :

- Either descriptive and scientific, designed for professional and practical users capable of combining the analytical data with a reasoning likely to answer their questions, such as : where is the water ? How much is there, in terms of flow and storage ? How can it be tapped, at what yield, at what cost ?
  The nature of the rocks (based on a hydrogeological typology), the climatic conditions, the hydrodynamic conditions, etc., are represented separately by conventional signs and colours. Economic interpretation, where possible, is left to the user's initiative.

- Or, more informative, in the sense that they offer more directly useable facts and answers adapted to certain practical questions, but are still "mono-thematic" : including vulnerability to pollution, water quality suitable for one specified use or a group of specific uses, or water cost. In the last case of a more directly "economic" map, the tests made to date, especially in West Africa, represent the zoning of a **cost** descriptor which has no relation to categories of water use and demand. Here again, the data used are shown separately. It is up to users to put them together and take advantage of them according to their own aims.

The second type included the maps entitled "Groundwater resource planning maps", followed by the more-extensive "Water resource maps" drawn up from 1975 onwards on the initiative of the ICHS and thanks to the aid of the French Government's Assistance and Cooperation Fund.

Published at a scale of 1:1,500,000 and covering most of the countries in West and Central Africa, these maps had the merit of attempting to show for the first time the hydrogeological knowledge at a given stage and as uncomplicated facts that were adapted to the user's needs, albeit paying the price of such simplification. From this point of view, they are the **roots** of the present maps to which they were a prelude. These maps could not, however, develop with the progress in knowledge nor with the changes of certain physical and economic conditions, thereby creating new questions in themselves.

Mapping, which has the express aim of **helping in decision making** on, e.g., the use of groundwater, should integrate all available information, enabling an assessment of this groundwater potential, which can only be expressed by reference to a synthetic value scale that is both :

- **unique,** in order to compare the resources contained in different regions, and
- **variable** in order to adapt to the criteria of different economic sectors.

Indeed, while such mapping is "pre-interpreted", it must allow future interpretation alternatives so as not to impose a single rigid option on the user, and it must also be easily updated. From this viewpoint, it appeared possible to identify characteristic quantitative components of the groundwater resource by **three main descriptors,** each associating **two physical factors** :

- the **accessibility,** expressing the effort and investment cost required to tap the groundwater resource, determined by the depth to be drilled and by the success probability of the wells ;
- the **exploitability,** connected with yield and length of the pumping column, in other words the well productivity, on which depends the choice of pumping technology used (ranging from manual to solar) and to which the notion of pumping-energy cost is attached ;
- the **reliability** of the supply, not only expressed as a function of demand, but also depending on the local capacity of the aquifer (reserve) and on the natural flow recharging it, expressed as an assured yield during a definite length of time.

It was seen that 62 % of the area is underlain by comparatively shallow, low-productivity aquifers in a fissured environment. It is this resource that must be assessed and classified with a view to development, which will still be of a local or "village" type. In this respect, these modest resources are generally suitable for a "self-centred" type of development. The assessment of such "low-grade" aquifers, which are the only one's available over two-thirds of the territory, depends on subtle techniques.

Based on the quantitative scales, calibrated in absolute values and specific to each of the six factors, it was possible to define conventional classes, which could be combined two by two to define ordinal classes, specific to each descriptor. These were, in turn, combined to build up a final, still ordinal, synthetic classification, applicable to the mapping according to the chosen criteria and weighting.

The map obtained represents, for a given period, the state of a still little exploited groundwater resource, which enables to assess the zones that are favourable for development. It is an **orientation document** and not a simulation model. It suggests nothing about the state of the resource at a later time, when rainfall and exploitation may have modified it.

I.1.2. Descriptors and factors

I.1.2.1. Accessibility or the catchment work-cost notion

The Accessibility descriptor aims at quantifying the amount of effort and thus the necessary investment needed to tap an aquifer. It combines two main factors that depend on the aquifer's nature and structure without taking into account, here, the geometrical and hydrodynamic parameters governing its productivity (I.1.2.2). The two factors are :

a. - The **depth actually dug or drilled** for the wells, taking into account the minimum penetration depth required to obtain the yield allowed by the aquifer on the one hand, but also the required supply, which is a function of the well characteristics.

b. - The **success probability** that can be attributed to a planned well, deduced from the results obtained under similar hydrogeological conditions by earlier drilling. This probability is usually at a maximum directly above generalized aquifers, whereas it can be very low for certain discontinuous hydrogeological environments.

While it is obvious to link the construction cost of a well to a depth in a given rock type, the "risk" factor also enters into this cost : both by the increased preparatory exploration effort it may entail and by the effect of the cost of "failures" on the average cost of the positive wells within a borehole programme. It goes without saying that the assessments of "success" and "failure" must be related to a "target yield", itself subject to the projected use, be it village-water supply, small-scale irrigation, etc. In the present version, this "target-yield" was chosen by reference to the target aim of the village drinking-water supply programmes, i.e. 0.7 m^3/h, which corresponds to the performance of the first manual pumps.

I.1.2.2. Exploitability or the exploitation cost notion

This second descriptor measures the effort of extracting the water per unit of produced volume, independently from the investment amortization considered previously. In physical terms of **energy cost**, it depends mainly on two factors :

a. - The maximum production **yield** obtained by a "state-of-the-art" well, which depends primarily on physical aquifer parameters such as permeability and thickness, i.e. the **productivity**. The actual yield will, in fact, depend on the projected use and may be subject to a lower limit, for instance in the case of village-water supply.

b. - The **pumping depth** during exploitation, which, in most cases, equals the depth of the dynamic level while pumping, relative to ground level. Drawdown below the static water level is known to depend greatly on the aquifer parameters.

In this interaction of the production yield and pumping depth, a similar idea to that of "specific yield" is recognized, which, however, is no longer related to the drawdown alone.

Obviously, this energy cost can be expressed as financial cost of exploitation per m^3 of water produced, account being taken of the thresholds that separate the various pumping processes (manual, thermo-electric, solar) and at a given date.

I.1.2.3. Reliability or the longevity notion of the exploitation

The third descriptor, reliability of supply, implies that the exploitation should not upset a dynamic balance between the water recharging the aquifer and the discharge, either through pumping or by natural flow. The time frame, inside which a certain temporary unbalance is allowed, depends on the relationship between the aquifer's local capacity, the **reserve,** and the average **inflow.**

The reliability can thus be just as well guaranteed in the case of an aquifer with minimum storage capacity, but which is amply and regularly recharged, as in that of an aquifer with low and irregular recharge (the general rule in arid zones) but with a great storage capacity. An aquifer that has a small capacity and is divided into compartments, as well as being irregularly recharged, can only offer reliable exploitation for very small yields.

The reliability descriptor can be defined by the interaction of two factors :

a. - The **recharge flow** to the aquifers, all the more irregular as the annual average is smaller, is expressed as annual volume per area unit and given as a height (mm/year). Where no estimate is available of this "continuous regional variable", it was accepted to use the calculated **effective precipitation,** in view of the very large-scale nature of the work undertaken. This means total theoretical potential flow : infiltration plus surface-runoff. For want of a more detailed knowledge of the infiltrated portion, an approximate proportional relationship was supposed between this index and the actual infiltrated flows, over the scale of several years. Obviously, at bigger scales the "run-off" component of river flow would have to be deducted to improve the adopted hydrometeorological index.

To draw up a map that represents the distribution of this index, the available climatic data were carefully treated : calculation based on daily data of 124 stations over a period of twenty years, which made it possible to draw the "effective isohyets" of 20 to 1,000 mm/year.

b. - The **groundwater volume or reserve** contained locally by the aquifers is expressed by a volume attributed to an area unit. In practice, rather than considering the total theoretical reserve of the aquifers over their entire surface (of which only part can be used), the considerably smaller volume was taken that can be withdrawn between two recharge phases, by pumping to the maximum drawdown allowed in the wells.

Combining these two parameters amounts to expressing the average turnover of the reserves by the inflow, in relation to the chosen time unit, which is a year in this case. The interannual regulating capacity of an aquifer, therefore its "resistance to drought", will be all the greater as its annual turnover frequency is higher.

I.2. THE STEPS IN INFORMATION PROCESSING

I.2.1. Choice of parameters

I.2.1.1. Accessibility descriptor

It was seen above (I.1.2.1.) that the catchment-work cost notion was naturally connected to the combination of two factors :

- the success probability in drilling the well,
- the actual depth drilled for this well,

it being understood that the assessment, of **success** and **failure** relates to a **target yield** which, itself, depends upon the planned use.

I.2.1.1.1. The success-probability factor

This factor was calculated as the arithmetic mean of the available data. It was difficult, in practice, to harmonize the recorded success rates, as different drilling programmes would have different concepts of such success rates. Thus there were :

a - wells whose yields reached or exceeded the contractual target yield ;

b - wells equipped for yields lower than those fixed by the schedule of conditions when, for example, the village water requirements proved to be small but vital ;

c - initially productive wells with yields higher than those fixed by the programme terms, but abandoned as a result of technical difficulties and which were or were not integrated into the original statistics expressing the success percentages ;

d - the fact that existing borehole equipment was taken into account in the financial evaluation of wells considered as **positive** ;

e - the integration of positive wells, outside the programme, in the success probability calculation.

While the last three cases prove to have an insignificant effect on the final success probability calculation, the first two can be quite significant. The difference noted between these two calculation hypotheses could be as much as 15 % of the overall result.

I.2.1.1.2. The well-depth factor

This was found by calculating the arithmetic mean or better still the median of the collected data. Nevertheless, the choice of the most suitable depth to be taken into account in the mapping was not made immediately, four questions presenting themselves :

a - Had the Total Depth of the well to be considered, regardless of hydrogeological conditions and technical constraints ?

b - Should not, on the contrary, the depth be taken at which the drilling ought to have been stopped, the "target yield" having been reached at a higher level than expected ?

c - Could the depth of the last water inflow constitute a limiting factor in discontinuous aquifer environments ?

d - How should one integrate (or not) **excessive** depths reached in wells drilled on sites that experience had clearly classed as unsuitable to any new exploration ?

Thus, depending on the nature of the programmes and the geographical sectors concerned, one or several of these four cases would influence the final calculations. Generalized and discontinuous aquifers were the subject of specific studies (I.2.2.1.).

As the **Accessibility** descriptor brings in a notion of catchment-work cost, the criteria chosen for selecting the most representative values logically express a real or potential cost, theoretically valid for perfect installation and working conditions, and not depending on subjective decisions of the hydrogeologist or driller.

I.2.1.2. The **Exploitability** descriptor

This second descriptor reflects the quantity of energy needed to withdraw a certain volume, independent of the previously mentioned cost. In energy or exploitation cost terms, this descriptor is therefore dependent upon two factors :

- the factor of productivity or yield, which can be potentially supplied from the well,
- the factor of pumping depth of the resource.

Both factors are closely dependent on the aquifer's lithological nature, and on its hydrodynamic and potentiometric properties.

I.2.1.2.1. The well productivity or yield factor

Distinguishing the value that is representative of a well production was a difficult task : the final selection of the productivity factor proved to be impossible. For this reason, and after thorough study of the data collected in the well-completion reports, it was decided, in view of the great heterogeneity in data presentation, to define an order of priority in the available statistical processing. This order starts with the best representativity and works down the scale.

a - **For the generalized aquifers :**
- median of the **yields measured during the pumping and/or development tests** carried out on the positive boreholes,
- geometrical mean of the same yields,
- arithmetical mean of the same yields.

b - **For the discontinuous aquifers in fissured environments :**
- median of the **yields measured during the pumping and/or development tests** when carried out on the positive boreholes,
- median of the **yields obtained at the end of drilling,**
- geometrical mean of the same yields,
- arithmetical mean of the same yields.

As these yield values are obtained under varying conditions (air-lift, or submersible electric pump), the information collected presents a great heterogeneity from one programme to another, but also within the same programme (effect of the pumping depths). For this reason, and to straighten the distortion observed when the information was processed, the productivity factor was combined with the factor of pumping depth, which can also be called extraction or drawing depth, or total manometric height (TMH).

I.2.1.2.2. The pumping depth factor

The mapped information was obtained from examination of :

a - the **pumping test results** (specific yields, dynamic levels under the test conditions) ;

b - estimations of the groundwater level **drawdown** at the end of drilling, calibrated on pumping test data from existing wells located in a comparable hydrogeological context ;

c - the **dynamic water level** logically acceptable from estimating the level of the main water-bearing horizons.

I.2.1.3. **The Reliability descriptor**

This descriptor expresses the relation between the aquifer's local capacity - in the sense of a groundwater reserve - and the average recharge of meteoric origin

(I.1.2.3.). The logical and classical approach is to characterize the resource quantitatively by the interaction of two factors :

- the mean annual effective rainfall factor, which forms a **recharge index** ;
- the aquifer's local reserve factor.

I.2.1.3.1. The mean annual rainfall recharge index

The available daily-rainfall records, supplied by ORSTOM, were collected at 124 stations set up in French and English-speaking West and Central Africa, over the period 1959-1983. The mean effective rainfall was calculated for each day over a 21-year (1959-1979) reference period, taking into account two easily-usable reserve values equal to 100 mm and 50 mm. This will be further developed in Part 2, section 1.2.

The effective infiltration approach was postponed, due to the present lack of information about various parameters entering into the calculation. It was, therefore, decided to present the simpler information consisting of the effective rainfall, which shows an acceptable analogy with the effective infiltration concept, considering the scale of the map area.

I.2.1.3.2. The aquifer's local reserve factor

This factor was determined from certain hypotheses of effective porosity and maximum-acceptable drawdown (in the case of generalized aquifers in sedimentary waterbearing environments), but also deduced from the saturated thickness of the porous formations lying on top of the fissured rock with a more limited storage (discontinuous aquifers).

The variability of this factor will have to be redefined when the necessary facts on the effective seepage and on distribution of pumped wells will be available. In practice, this factor is estimated by taking into account localized observations (unfortunately few) but also by integrating information deduced from the water resource planning maps drawn up in the seventies at the initiative of the ICHS.

I.2.2. Descriptor classification process

The mapping undertaken consists in defining elementary areas that are considered to be homogeneous from the viewpoint of the different factors that were enumerated above, whose outlines are traced on the map. The following step is to give each area a synthetic resource class. The aim, therefore, is to create an appropriate

classification from the described factor typology and from the combination of factor-couples as descriptors.

The first stage of the classification process is the careful working-out of three classification **matrices**, corresponding to each descriptor and its pair of factors, the quantitative scale of each factor being divided by 3 numerical **breaks** or **threshold** values into 4 classes and shown in the following sections according to a progression from less favourable to more favourable conditions.

I.2.2.1. The **Accessibility** descriptor (table 1)

Classes	Work depth factor (m)		Success probability factor (%) for a target-yield of at least 0.7 m^3/h
	Discontinuous aquifer	Generalized aquifer	
I	> 85	> 250	< 50
II	85 - 65	250 - 100	50 - 65
III	65 - 45	100 - 50	65 - 80
IV	45 - 0	50 - 0	> 80

Table 1 - Variability classes of the Accessibility descriptor

The threshold values of the well depths were defined from field data but also from technical criteria concerning the type of catchment work and specifications of the drilling rigs. The success-probability values are also deduced from the results of completed drilling programmes and according to the variability of the success rate, which can be seen as a function of the geological environment.

The result of the interaction of these two factors is shown on the map entitled **"Accessibility Descriptor"** (in pocket).

I.2.2.2. The Exploitability descriptor (table 2)

Classes	Pumping depth factor (m)	Productivity or yield factor (m^3/h)
I	> 50	0.7 - 2
II	50 - 20	2 - 5
III	25 - 10	5 - 10
IV	< 10	> 10

Table 2 - Variability classes of the exploitability descriptor

The variability of the pumping depth factor depends mainly on the nature of the resource-tapping device, the latter, obviously, being chosen according to the individual hydrogeological conditions. A classification was then made of the withdrawal (i.e. pumping) means according to the maximum depth of the water level during pumping. Table 3 shows the relation between the various pumping devices and pumping depth in the present mapping.

Generally accepted pumping depth intervals (m)	Pumping devices
0 - 10	. Surface suction-force pump . Any other means of manual or animal drawing
10 - 25	. Man-worked pump . Other submersible or surface devices
25 - 50	. Man-worked pump, knowing that the resource extracted will be extremely low. The physical limit for using such devices cannot exceed extraction depths of over 50 m
> 50	. Motor-driven pumps (electric submersible pumps, vertical axis pumps, driven by thermal, solar, or wind energy)

Table 3 - Relation between pumping devices and pumping depth

The results of the interaction of the pumping depth and productivity factors is reproduced on the map **Exploitability Descriptor** (in pocket).

I.2.2.3. **The Reliability descriptor** (table 4)

Classes	Local aquifer reserve (thousands of m^3/km^2)	Index of mean annual effective recharge (mm/year)
I	< 75	< 150
II	75 - 150	150 - 325
III	150 - 225	325 - 450
IV	> 225	> 450

Table 4 - Variability classes of the Reliability descriptor

The notion of the local reserve of an aquifer represents the outcome of a long period of reflection, which began with the drawing up of the water-resource planning maps. For this reason and because of the insufficient amount of data on the withdrawals, the **regulating capacity** notion, characterized by the number of pumping years without recharge, was modified. The mapped representation of this notion was consequently limited to the physical factor **local aquifer reserve,** only. This expression obviously restricts the notion of volume that is effectively exploitable on a regional scale.

The calculation of the effective rainfall made it possible practically to eliminate any influence of rainfall distribution in time, regardless of season. Obviously, the recharge only represents a portion of the effective rainfall, also depending on soil and rock types encountered, as well as the morphology of the terrain.

The effective rainfall thus only provides an **index** of the recharge. The combination of the two factors reserve and recharge is shown on the map **Reliability Descriptor** (in pocket).

I.2.2.4. The water-potential map : a final **synthesis** (fig.1).

The 16 possible cases of each matrix were divided into four groups, each forming an ordinal class of the descriptor under consideration and marked from 1 to 4, from the "least favourable" to the "most favourable". These "marks" will have the value of **points** in the final combination ; the reader should understand that this type of marking is but one of many possible systems.

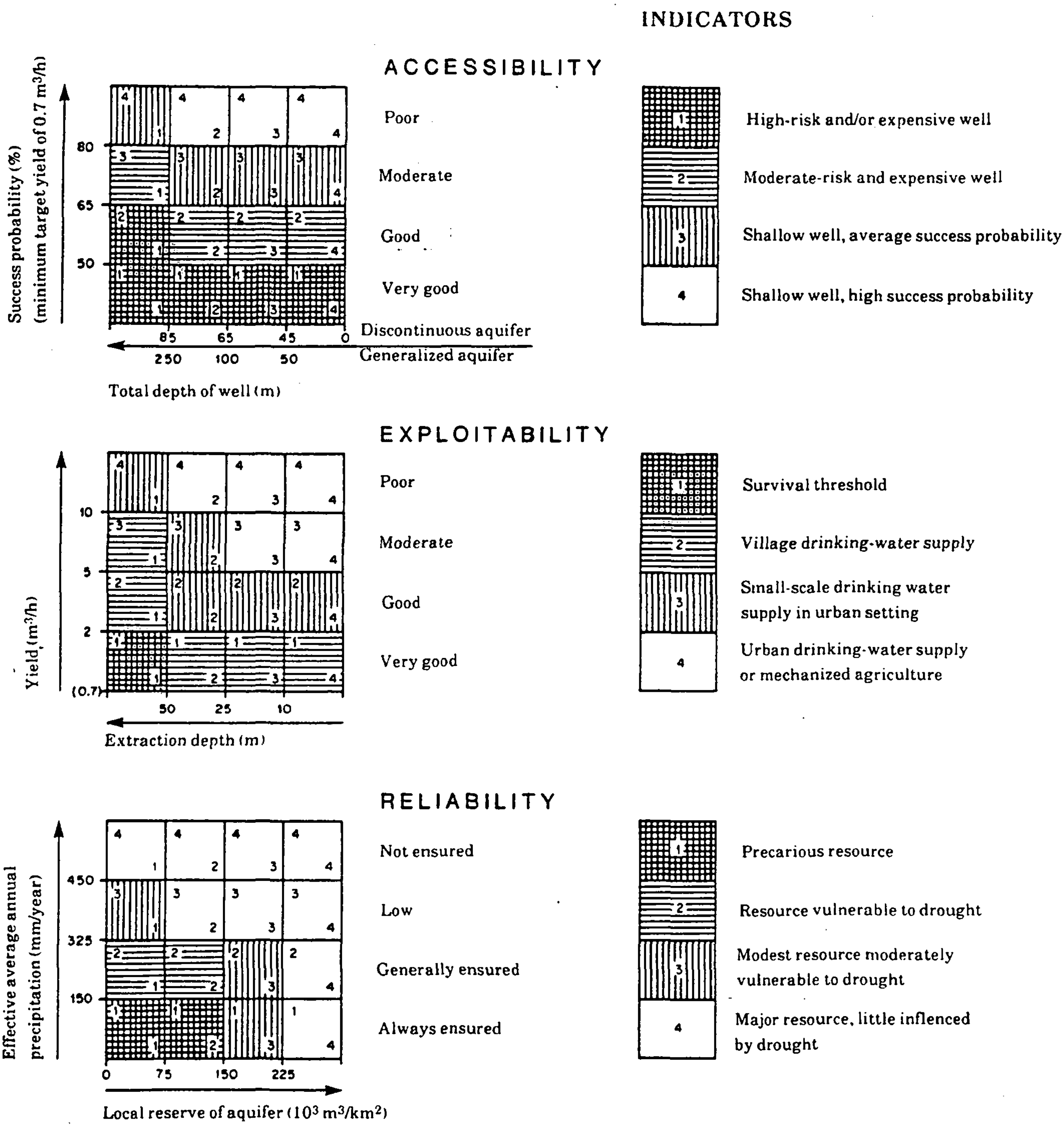

Figure 1 - Classification matrices of the three descriptors

Determined from the matrixes for each of the three descriptors, and of three thresholds determining four categories numbered 1 to 4, 1 being the least favourable and 4 the most favourable

2-1, 2-2, 1-1, 1-2 etc. are marks given for the two associated factors representing a given descriptor, 1 being the least favourable and 4 the most favourable

This leads to the stage of combining the said ordinal classes to arrive at the construction of the final synthetic classes of groundwater "potential". This combination starts by simply adding the "marks" attributed to a given area for each descriptor and finishes with the definition of four new ordinal classes of potential whose distribution, after definition of a final "mark", is as shown in table 5.

Number of points	Classes	Potential grades
3 to 4	I	Unfavourable formation, limited to potable water exploration only on identified structures
5 to 7	II	Not very favourable formation, rather uneconomic and poor possibilities, high failure risk
8 to 10	III	Favourable formation, possibilities of advantageous development, at a small risk
11 to 12	IV	Very favourable formation, excellent possibilities of development presenting good economic return and minimum risk

Table 5 - Classes of water resource potential variability

This classification was used to draw up the final map, but it is only one of several possible options. For example, it would be perfectly feasible to add weighting coefficients to each descriptor (equal in this case) or to introduce other relative divisions. A clear distinction must be made between the general principles of the planned classification process and the special options chosen for its present application among other possible processes. This thematic mapping notion, in fact, allows a large variety of possible representations, adapted to specific requests.

I.2.3. Computer-assisted mapping

The planned classifying mapping of groundwater-resource potential with its multi-optional possibilities and its adaptability for users could not have been developed without the material support of the modern graphic data-processing equipment. This enabled :

- automatic combinatory calculations from data bases, the parameters for each factor, attributed to all the elementary areas (SYNERGIE software, developed by BRGM) ;
- the automatic tracing of the boundaries of these areas after coding their outlines, on any scale whatsoever ;

- classification of the potential of each area, according to a chosen "scale" (such as that adopted and shown in fig.1).

The drawing of a unique synthesis map, to be published in this case at a scale of 1:5,000,000, which allows a simple, panoramic visualization of the groundwater potential, must highlight the innovate character of the process, the fact that this is **mapping that aims at becoming conversational :**

- freed of the material constraints of printing at a single scale only ;
- easily corrected, and updated ;
- changed on request, according to the choice of the different possible alternatives from the classification and weighting criteria.

This new mapping thus transcends the traditional technique, which produced a fixed map with an inflexible key, a "passive" medium of information offered to the reader, a map whose revision was laborious and expensive.

In the future, instead of a simple map, there will be a **graphic data** base that can be questioned by software, which produces maps on request and which can be modified by the introduction of new information. The interactivity, which exists between the user and the system, **will offer a decisional and tailor-made capacity** by the information it will restore instantaneously.

This map-making concept presents therefore a constantly evolving universal character. Nevertheless, the financial commitments of the present project obliged us to terminate the graphic data base on 31.12.1985 ; the **"development potential from groundwater resources"** presented here can thus be compared to a "frozen" image in a film based on the development scenario. This image, which concerns the observed hydrogeological environment can be started up again at any time by an updating of the graphic data. The present map should be seen as an **example** rather than as a unique result at the scale of the 23 countries concerned ; beyond this lies the wide scope of the possibilities of reasoned alternatives that remain wide open, notably at the scale of the national territories (cf Part 3, § 2).

I.2.4. Quality and representativeness of the information

I.2.4.1. Bias in basic data and their results

The quality and representativeness of the information mapped within the present contract was found to be biased because of the diversity characterizing the studied production programmes. The reasons for this are :

- the well-siting criteria for each programme usually are different from one programme to another ;
- selection of the area where all or part of the programme takes place is normally biased towards a selection made a priori ;
- on the contrary, many study areas discarded for earlier operations were retaken into consideration in view of the new development plans ;
- lastly, the variable quality of execution and supervision of works undoubtedly has a negative effect upon the reliability and the representativeness of the acquired data.

As an example, more care in site selection (remote-sensing photo-interpretation, structural analysis, geomorphology, geophysical prospecting, etc.) will not necessarily compensate for the low hydrogeological potential of the village sites turned down during earlier programmes, the best sites having been given priority.

The available mapped data here **are thus of unequal quality.** This is why it is necessary to evaluate the results subjectively when carrying out their comparative analysis prior to mapping. In spite of its slightly empirical nature, this step cannot be avoided.

I.2.4.2. Representativeness of the hydrogeological potential

The data obtained from the execution of a hydrogeological work programme are not always characteristic of the rock types in general, but rather of lithological and structural anomalies present in these rocks.

The data selected for the present mapping are thus commonly connected with the discontinuities that may exist within a single rock-type and with the disturbing influence such discontinuities can have on percolation, storage, and permeability, in other words on the exploitation conditions of the resource. For this reason, the drilling-programme results will dominate in the definition of the exploitation conditions, rather than natural criteria such as geomorphology, rock type, or fracturing and weathering conditions of the rock.

Part II

DATA ACQUISITION AND PROCESSING

II.1. CLIMATE AND PRECIPITATION DATA

The small-scale map making was carried out in several stages :

- reading from magnetic tape or manual acquisition of meteorologic and climatic data needed for calculating the potential evapotranspiration (PET) by the **Turc** method ;
- selection of the rainfall stations so as to obtain the most reliable data possible over the longest common period ;
- calculation of the effective rainfall over all selected stations for two useful reserve (UR) hypotheses fixed at 50 and 100 mm.
- automatic mapping.

II.1.1. Data acquisition

The acquired data were taken :

- from magnetic tape provided by ORSTOM and including the daily rainfall figures observed at 155 stations scattered throughout Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Congo, Gabon, Ivory Coast, Mali, Mauritania, Niger, Senegal and Togo. These 155 stations already represented a selection of the most reliable stations made by ORSTOM ;
- from miscellaneous sources, which include the climatic data available in Nigeria and those required to calculate the PET (monthly temperatures and insolation observed at the 155 selected sites).

Unfortunately, it was not possible to obtain sufficient climatological data for Ghana, Guinea Bissau, Guinea Conakry, Equatorial Guinea, the Cape Verde Islands, Liberia, Sao-Tome and Principe, and Sierra Leone. For these countries, daily rainfall figures (incomplete) were available over the 1953-1983 period, but the other climatic data were usually only available as monthly averages per year. This was the case also for the Nigerian rainfall data.

II.1.2. Selection of meteorological data

The selection of the rainfall-gauging stations of French-speaking Africa was made on the following criteria :

- the initial reference period (1959-1983) was changed to 1959-1979 as less than 10 per cent of the stations included information on the 1979-1983 period ;
- a year was considered as **doubtful** when the gaps in the measurements stretched over at least 60 days ;

- a station was kept when there were less than two **doubtful** or **missing** years over the 1959-1979 period ; in this case the effective rainfall sequence was not interrupted (the missing data being replaced by their observed interannual mean), but the interannual effective rainfall figures were calculated on the reliable years only ;
- in the situation where less than 60 days' interruptions of measurements appeared during a year, the missing data were replaced by their observed interannual mean, the 1959-1979 period being used then for calculating the mean annual effective rainfall.

Thus, 114 stations were retained out of the 155 proposed by ORSTOM. They are shown in appendix with their coordinates, by country. It is to be noted that the interannual means of the monthly PET are also available for these 114 stations. In Nigeria, 10 stations were selected because of their long observation periods ; their names are given also in appendix.

II.1.3. Calculation of the mean annual effective rainfall

For each chosen station, a **daily assessment** was made over the 1959-1979 period, admitting that the potential evapotranspiration (PET) of each day of the month was equal to one-thirtieth of the PET of the month.

These calculations were made for two "useful reserve" values, 100 and 50 mm. Without going into detail it should be emphasized that, whatever the chosen "useful reserve", effective rainfall maps are obtained with a range of $\pm$ 50 mm, which consequently all show the same abundant or poor rainfall zones from the effective rainfall viewpoint. In this case, the 100 mm **useful reserve** was adopted.

II.1.4. Recharge assessment

The assumption is that the calculation of the mean annual effective rainfall made it possible to eliminate, in its entirety, the influence of the rainfall distribution in time regardless of season. The recharge is, therefore, a proportion of the effective rainfall, even though it is not linear as it depends mainly on the aquifer lithology and the surface morphology.

The spatial distribution of the effective rainfall is independent from the rock types and morphology encountered. This is not the case, however, for the recharge, which may be only 30 to 70 % of the effective rainfall depending on the morphology and rock types at surface as well as at depth.

While awaiting the results of the studies in progress under CEC financing, the mean annual effective rainfall is a good recharge index as a zone with a high effective rainfall usually has a high recharge. This is not true when only the gross rainfall is considered.

II.1.5. Automatic mapping of the interannual mean effective rainfall

Automatic mapping of the effective rainfall isohyets was carried out for the 124 stations studied, using the UNIRAS LUCAS software developed by BRGM. The map of the average yearly effective rainfall, worked out with the hypothesis of a usable reserve of 100 mm, is shown in figure 2. The isohyets are seen to be markedly closer together above Sahelian Africa, north of which zone the effective rainfall figures are everywhere below 20 mm, whatever the longitude.

As the effective rainfall isohyets of 150, 325 and 450 mm, which were used to quantify the index of "mean annual effective rainfall", enter into the definition of the **Reliability descriptor map**, they have been removed from the effective rainfall distribution mapping presented in figure 2. Their "divisional" value was determined during the first approach, from various experimental observations.

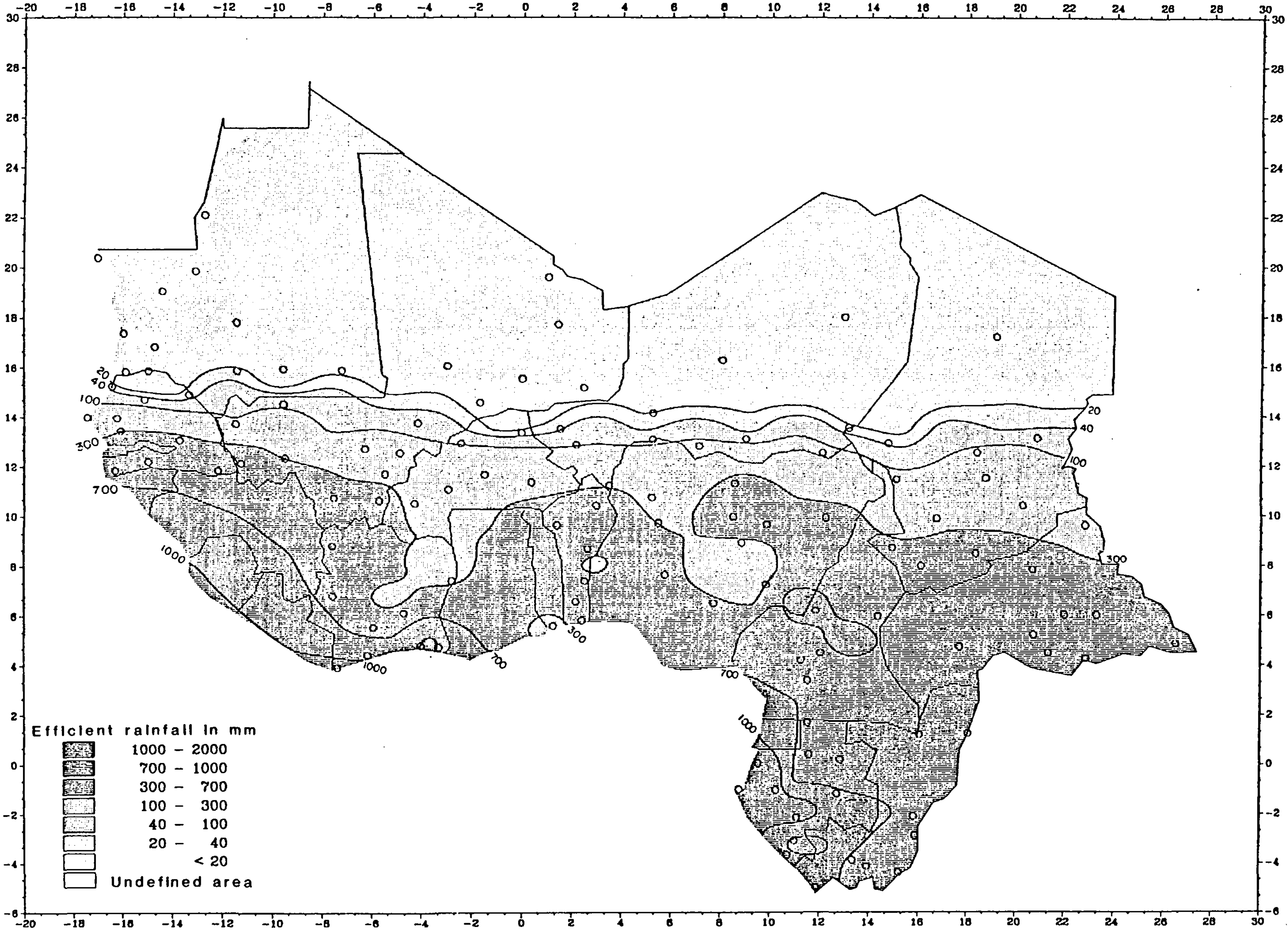

Figure 2 - Map of average yearly effective rainfall

II.2. ELEMENTS CHARACTERIZING THE GROUNDWATER RESOURCES

II.2.1. The major lithological units

The geological background used for the four maps presented, consists of mapping of the rock types which is different from a conventional geological map by the **absence of chronostratigraphical criteria.** The formations of different ages were thus assembled when they presented similar rock type and a similar hydraulic behaviour.

The major units defined in this way may be distinguished primarily by their aptitude to deformation or their degree of plasticity. Table 6 below gives a summary of the rock types adopted for the maps, which derives from information supplied by the existing geological maps.

Rock Type	Aptitude to deformation
Sand Clayey sand Sandy clay Clay and marl Calcareous clay	Plastic sedimentary
Clayey sandstone Sandstone Calcareous sandstone Limestone Marly limestone Dolomite	Sedimentary with moderate tendency to become deformed
Schist Quartzite Conglomerate Volcanic rock Dolerite Metamorphic rock Granite	Formations of varied origins which cannot be easily deformed but are apt to break

Table 6 - The major lithological units adopted in the mapping

II.2.2. The major hydrogeological units

Hydrogeological units depend on the distribution of lithological units ; in view of the very small map scale (1:5,000,000), the classification was reduced to three major groups shown in table 7 below. The two major aquifer types encountered, generalized and discontinuous, are seen in this table, associated with a third group whose distinctive feature is its mixed hydraulic nature, generally depending on local conditions.

In detail, in a major hydrogeological unit, each rock type actually makes up a hydrogeological sub-unit, inside which the descriptors and factors are taken to be constant, or without much variability. Table 8 shows the proportional distribution of each aquifer type in each country.

Rock type (hydrogeological sub-units)	**Type of aquifer** (major hydrogeological units)
Sand Clayey sand Sandy clay Clay and marl Calcareous clay	Generalized or with continuous groundwater
Clayey sandstone Sandstone Calcareous sandstone Limestone Marly limestone Dolomite	Mixed character
Schist Quartzite Conglomerate Volcanic rock Dolerite Metamorphic rock Granite	Discontinuous or with local groundwater

Table 7 - Main hydrogeological units adopted for the mapping

II.2.3. Productivity of the main rock types (specific yield)

The productivity of a type of formation can be expressed by the yield supplied per metre of drawdown, also called the specific yield of a well. This notion appears indirectly in the groundwater-potential map by means of the exploitability descriptor, the latter resulting from the interaction between the factors of well yield and resource- extraction depth. The classification of the specific yield values per lithological rock type unit is shown in table 9, which shows the close relationship between the specific yields obtained and the rock type.

Country	Surface area	Generalized aquifers		Mixed aquifers		Discontinuous aquifers	
	km²	%	area km²	%	area km²	%	area km²
Benin	112 622	10	11 262	12	13 515	78	87 845
Burkina Faso	274 200	4	10 968	12	32 904	84	230 328
Cameroon	475 442	20	95 088	18	85 580	62	294 774
Cape Verde Is.	4 033	--	--	--	--	100	4 033
Central African Rep.	622 984	18	112 137	8	49 839	74	461 008
Chad	1 284 000	60	770 400	22	282 480	18	231 120
Congo	342 000	27	92 340	64	218 880	9	30 780
Gabon	267 667	1	2 677	52	139 187	47	125 803
Gambia	11 295	83	9 375	17	1 920		
Ghana	238 537	6	14 312	40	95 415	54	128 810
Guinea Bissau	36 125	40	14 450	60	21 675	--	
Guinea Conakry	245 857	1	2 459	27	66 381	72	177 017
Guinea Equatorial	26 017	4	1 041	4	1 041	92	23 935
Ivory Coast	322 463	4	12 899	--	--	96	309 564
Liberia	111 500	2	2 230	--	--	98	109 270
Mali	1 240 710	52	645 169	37	459 063	11	136 478
Mauritania	1 030 700	50	515 350	23	237 061	27	278 289
Niger	1 267 000	66	836 220	26	329 420	8	101 360
Nigeria	923 768	25	230 942	15	138 565	60	554 261
Sao Tome and Principe	955	--	--	--	--	100	955
Senegal	201 400	64	128 896	28	56 392	8	16 112
Sierra Leone	71 740	12	8 609	10	7 174	78	55 957
Togo	56 000	8	4 480	16	8 960	76	42 560

Table 8 - Distribution in percent (and estimated surface) of the major hydrogeological units for each country

Rock Type	Specific yield ($m^3/hr/m$)			
	Yield range			Average
Environment dominated by generalized aquifers				
. Clayey sand	1.30	to	25.0	14.0
. Pliocene clayey sand (Chad)	0.10	to	23.0	11.0
. Cretaceous sandstone (Cameroon)	0.90	to	15.0	8.0
. Quaternary (Chad, coastal basins)	0.07	to	20.0	7.0
. Dolomite (Gabon)	4.70	to	6.3	5.5
. Paleocene limestone	2.40	to	12.6	5.5
. Undifferentiated sandstone	0.13	to	10.0	3.5
. Clayey sandstone (K-T)	0.01	to	15.8	2.5
. Clayey cretaceous	0.12	to	4.0	1.5
. Claystone, pelite	0.20	to	1.7	0.8
Environemnt dominated by discontinuous aquifers				
. Schist	0.10	to	1.15	0.50
. Undifferentiated granite and gneiss	0.01	to	1.90	0.40
. Gneiss	0.10	to	0.40	0.30
. Micaschist	0.08	to	0.50	0.30
. Old granite	0.02	to	0.50	0.25
. Quartzite	0.20	to	0.30	0.25
. Migmatite	0.10	to	0.15	0.10
. Young granite	0.13	to	0.50	0.10
. Clayey sandstone	0.12	to	0.16	0.10
. Dolomitic limestone	0.11	to	0.15	0.10

Table 9 - Distribution of specific yield for each rock-type unit

II.2.4. The success probability according to rock type (table 10)

Taking only natural phenomena into account, the rock type and the rainfall both have a marked influence on the success rates registered during well drilling within the village-water supply programmes.

Thus, for each rock type, weathering will be more or less developed depending on the climate, which adds an additional variable to the probability of finding sufficient groundwater.

Rock type	% success rate		Countries and overall success rates (%)		Type
	Average	Mini-maxi			
Coastal sand Coastal basin Valley alluvium Wadis	> 80	80 to 93	Ivory Coast (93) Niger (>80)	Chad (>80) Nigeria (>80)	
Clayey sand (KT)		0 to >80	Benin (50 to 100) Mauritania Congo	Senegal	Good
Old Quaternary	>80	>80	Chad		
Clayey sandstone		70 to 100	Guinea (70) Benin (80-100)	Mali (70)	
Clean sandstone		50 to >80	Mali (>80) Chad (>80) Nigeria (>80)	Mauritania (50-65) Congo (>80)	
Sandy clay	80	–	Mali	Niger	
Marly limestone	80	75 to >80	Senegal (>80) Benin-Togo (>75)	Mali (80)	
Clay	75	<50 to >80	Benin (>75) CAR (65 to 80)	Mauritania (>80) Gabon (<50)	
Limy. sandstone Limestone	75		Mali (<50)	Gabon (65 to 80)	
Schist	75	50 to 95	Ivory Coast (85) Sierra Leone (57) Burkina Faso (65 to 90) Mauritania (50-60)	Guinea (85-95) Mali (75) Niger (67 to 85) CAR (60-80)	Fair
Granite	75	55 to 85	Ivory Coast (77) Guinea (75) Benin (60-80) Burkina Faso (65-85) Niger (57 to 84) Cameroon (60-80) Guinea Equatorial (75) Nigeria (80)	Ghana (55) Liberia (62-67) Togo (60-80) Mali (67-80) Chad (<50) Congo-Gabon (50-75)	
Metamorphic rock	65	<50 to 80	Togo-Benin (58-74) CAR (50-65) Nigeria (50-80)	Mauritania (50) Guinea Equatorial (65-80)	
Volcanic rock	<65	<50 to 85	Benin Chad	Senegal	Moderate
Quartzite		25 to 74	Benin Ghana	Togo	
Dolomite	60	<50 to >70	Mauritania (<50) Gabon-Congo (65 to >80)	Mali (<50)	
Dolerite	<60		Guinea (57)	Burkina Faso (60)	
Conglomerate	50		Mali	Benin	
Clayey sandy piedmont deposits	< 50	0 to 50	Cameroon	Chad	Poor

Table 10 - Distribution of success probability for a well based on rock type

II.2.5. Water quality

Most of the groundwater of West and Central Africa is very little mineralized (average dry residues equal to 326 mg/l) and characterized by a slight acidity. All this water is generally agressive and poor in chloride and sulphate, except in a few special cases such as in aquifers near the coast intruded by saline water or at the edge of sedimentary basins, places of concentration of mineral salts by evaporation. Their chemical rock type is commonly of the calcic bicarbonate or sodic type. Alkalic earth tendencies characterize the groundwater coming from volcano-sedimentary rocks. Sodium chloride occurs in water within the Precambrian gneiss of the Accra plain in Ghana.

Systematic analyses were carried out for certain elements such as iron and fluor within the Village Water Supply or Urban supply programmes in most of the West and Central African countries. Table 11 gives the average contents of the main chemical elements present in the water coming from a few geological formations encountered in West and Central Africa.

As a result of numerous studies comparing well water, which mostly is of near- surface origin, and borehole water commonly of deeper origin within bedrock, an idea of the chemical stratification of the water in discontinuous environments was obtained (table 12). For example, the borehole water differs from well water by higher ionic charge, pH and conductivity. This indicates a probable "stratification" of the groundwater, implying in itself a lateral flow without mixing of the levels. Similarly, the homogenization of the water by ion diffusion occurs slowly, is independent of the substratum and is also permanent.

Alternating dry and rainy seasons introduce variations in the physical-chemical characteristics of the groundwater. The dilution phenomenon brought about by the rainwater recharge reaches its climax at the end of the wet period. It is also seen that the minimum concentration for the various elements does not always coincide with the period of maximum rainfall, but can be delayed to occur at the beginning of the dry season during the groundwater depletion phase.

The **International Drinking Water Supply and Sanitation Decade** (1981-1990) has the goal of guaranteeing for everyone a supply of the cleanest possible water, which implies that the water must be of an irreproachable physical-chemical and bacteriological quality. The fact that water has low conductivity does not necessarily

AGE AND ROCK TYPE	Nb.	Conductivity µS-cm1	Temp. °C	pH	AVERAGE CONTENT in : mg/l														COUNTRY AND REFERENCES
					Na^+	K^+	Ca^{++}	Mg^{++}	HCO_3^-	SO_4^{--}	Cl^-	SiO_2	Mn^{++}	Fe_{tot}	Al^{---}	F^-	NO_3^-	Dureté	
Cambro-Ordovician Sandstone	8	190	22	6,5	3,8	0,65	19,5	5,7	98,4	< 0,5	4,1	—	—	1,5	—	—	1,5	—	Guinea (Conakry)
Voltaian Quartzite, shale, arkose, Tamale	65	—	—	6,9	84,7	—	38,4	11,0	—	6,9	12,2	25,0	0,26	2,0	—	0,3	0,3	70	Ghana
	7	—	—	7,9	44,04	—	28,3	5,7	—	112,9	279,5	30,9	0,66	0,68	—	2.24	0.22	67	
Buem Shale, arkose, sandstone and lava	37	—	—	6,92	27,5	—	35,3	17,5	—	1,42	4,78	49,8	0,58	0,34	—	0,17	0,35	183	Ghana
Atakora Quartzite, shale, phyllite	25	—	—	6,98	24,7	—	57,9	32,1	—	23,8	37,5	33,0	0,3	0,99	—	0,30	1,17	206	Ghana
Tarkwaian Phyllite, conglomerate	10	1000	—	6,9	—	—	—	—	107	—	32,8	—	0,00	0,15	—	0,08	0,01	78	Ghana
Birrimian Volcano sedimentary greenstone schist, amphibolite	10	400	—	7,9	—	—	—	—	—	—	—	47	—	—	—	—	—	—	Haute Volta
	2	—	—	7,3	37,0	1,5	52,0	50,0	597,0	0,14	3,0	120	—	—	—	—	—	—	Ivory Coast
Birrimian Granite	18	380	31,1	6,58	28,1	4,3	24,2	14,5	206,2	9,1	6,7	79,4	—	0,60	0,075	0,89	11,7	—	Ghana
Dahomeyan Schist and gneiss	13	3400	29,2	7,3	526,9	19,1	148,5	128,8	521,4	175,7	986,6	43,2	—	2,04	0,205				Ghana

Table 11 - Main physical-chemical properties of water within the basement and the old sedimentary rocks of West Africa

after: CEFIGRE, 1983/3 "Synthèse des connaissances sur l'hydrogéologie du Socle cristallin, crystallophyllien et du sédimentaire ancien de l'Afrique de l'Ouest"

Section	Aquifer	pH	Conductivity at 20°C m-cm^{-1}	Mineralization mg/l	SiO_2 mg/l	$\frac{Mg^{++}}{K^+}$	Ionic charge meq/l
Upper level (well)	Water contained in alluvium and weathered rock	6.51	23.6	37.9	21.5	1.38	0.87
Middle level (borehole)	Water in granitic sand (stone)	7.19	125.5	122.6	38.5	0.64	2.24
	Water in sand (stone) from greenstone and schist	7.63	172.2	165.2	49.7	3.05	4.84
Lower level (borehole)	Water within greenstone and fractured schist	7.94	404.2	326.1	61.7	36.7	11.9

ionic charge : sum of cations and anions in meq/l

Table 12 - Average values of several physical-chemical parameters of different waters in a basement area

from : CEFIGRE 1983/3 : "Synthèse des connaissances sur l'hydrogéologie du socle cristallin, cristallophyllien et du sédimentaire ancien de l'Afrique de l'Ouest"

mean that it is fit for drinking : there may be high contents of nitrate and trace elements (fluor, manganese, iron) making it unsuitable for human consumption. The need of a routine and complete chemical analysis of the groundwater can thus be seen.

In sedimentary basins, the shallow aquifers consisting of recent formations can suffer from seawater intrusion near the coast. In delta areas (Senegal, Nigeria), this invasion may reach several hundred kilometres. Because of the small map scale, this phenomenon is not shown on the enclosed maps, but for this question the maps of water resource planning aptitude might be consulted, which were drawn up under the auspices of the ICHS between 1975 and 1979.

High salt concentrations, caused by ancient seawater incursions and the concentration of mineral salts through evaporation, in places affect part of the interior sedimentary-basin aquifers. This is the case in :

- **Mauritania** : the saline groundwater of the Mauritanian basin ;
- **Mali** : the groundwater of the Taoudeni basin (northern Azaouad) ;
- **Niger** : the alluvial aquifer of Dallol Bosso, that of the Tégama, and the sandstone aquifer of the Agadès region ;
- **Senegal** : the Maastrichtian aquifer in its western half ;
- **Chad** : several shallow aquifers (such as near Lake Chad and in the Eastern Kanem), as well as the medium-depth pressurized aquifer of the Lake Chad basin.

II.3. GROUNDWATER USE AND EXPLOITATION

II.3.1. Comments about the groundwater-potential map

The groundwater-resource potential map (coloured, in pocket) shows that satisfactory potential exists on the scale of the 23 countries considered in this study.

Once again, it should be clearly stated that only the resource potential of shallow aquifer formations was distinguished during this study, in other words those that are intersected first when drilling or well-digging. The maps presented thus relate primarily to the "Village Water Supply" type of development and do no justice to the high potential of the deep aquifers within the great sedimentary basins, traditionally reserved to large-scale hydro-agricultural or industrial developments.

The primary reason for this choice was that the large potential that exists within the great sedimentary groups would have masked the much smaller potential of areas with discontinuous aquifers. It was therefore decided to use graphic overlays localized over certain sedimentary basins, to show the presence of deep aquifers where the possibility of obtaining yields at least equal to 50 m^3/h can be considered as reasonably certain. The basins in question are the Senegal-Mauritania basin, those of Niger, Nigeria and Chad, the small coastal basins of Togo and Benin, the small basin of the Benoué in Cameroon, the very large coastal basin of Nigeria, and the thick sedimentary succession of Ouadda in the Central African Republic.

As could be expected, this potential is lowest in the Sahel and then especially so in granitic or, more generally, "basement" areas like the "Adrar des Iforas" in Mali, the Aïr in Niger, and the volcanic massifs of Tibesti, Ouaddaï and the Guéra in Chad. All these areas are class I, attributed to all areas with a total number of points between III and IV (fig.1). It should be understood that all these areas, though unfavourable from the point of view of groundwater potential, nonetheless contain a certain, albeit limited, groundwater resource. Its exploitation, however, must be limited to drinking water only, from structures that are identified as likely to be water-bearing, which can be augmented by alluvial and piedmont aquifers that are recharged by rainwater and floods.

South of the Sahel lies an east-west ribbon of country with low groundwater potential, not very favourable and with restricted economic possibilities (class II of fig.1, attributed to all the areas with a total number of points between 5 and 7 in the ordinal classification adopted). The geographical distribution of this zone depends obviously on the rainfall in these regions, which is rarely over 500 mm. The groundwater potential of class II is sufficient for village-water supply, but will not tolerate even small hydro- agricultural development.

A little further south lie the areas of good groundwater potential (classes III and IV), covering the greater part of the territory concerned by the mapping. The aquifer formations in these areas present advantageous development possibilities with only moderate failure risks. The groundwater resource potential is greatest within the great sedimentary basins that contain generalized aquifers and development possibilities here present a good economic return with very low failure rates.

II.3.2. State of groundwater development

In the countries with high rainfall, surface water and springs are still intensely used for drinking purposes (3,770 villages in Nigeria) as well as shallow wells dug in stream beds. To satisfy the drinking water needs of the estimated 141,280,000 rural inhabitants in 1990, about 360,000 water points would be needed (an average of one for 393 inhabitants). This would mean creating 210,000 catchment works. Nigeria has half this rural population and would need more than 100,000 new water points.

To the requirements of village-water supply must be added those of the urban population, which represents a quarter of the estimated total of 202,500,000 inhabitants by 1990. The state of development of the different aquifers and the assessment of the need for new water points from now to 1990 is given in table 13. For village water supply, the density of existing water points is relatively small faced with the surface areas of the countries, varying from 1 water point for 10 to 100 km^2. Moreover, manual extraction limits the water volume withdrawn to 4,000 m^3/year/water point, which is negligible considering the volume brought into play by the natural water cycle (3 per mil in wet zones to 4 per cent in arid regions on a rainfall basis of 100 mm/year). Thus, except for concentrated motorized pumping on a certain number of boreholes, the existing village water supply only uses a very small portion of the renewable resources, including those in areas of limited recharge. Most of the fluctuations noticed orginate in a natural flow "loss" and not in consumption. The problem of "overdevelopment" is only posed in terms of local concentrations, but it is topical as it is precisely this type of development that might enable the improvement of agricultural production by irrigation.

On the other hand, a considerable phreatic decline can be seen in aquifers inside the great sedimentary basins, associated with an overdevelopment of the most productive zones (Senegal, Nigeria, Chad).

Country	Benin	Burkina Faso	Cameroon	Cape Verde	Central African Rep.	Congo	Ivory Coast	Gabon	Gambia	Ghana	Guinea Bissau	Guinea Conakry
Surface (km^2)	122 622	274 200	164 086	4 033	622 984	342 000	322 463	266 667	11 295	238 537	36 125	245 857
Population												
. total 1990	4 750 000	7 310 000	2 669 000	350 000 ?	2 800 000	1 940 000	12 568 000	1 030 000	793 000	12 600 000	670 000(?)	5 800 000
. rural 1990	3 600 000	6 580 000	2 104 000	--	1 890 000?	860 000?	5 670 800	250 000?	--	13 670 000	502 000(1)	4 600 000
Nb villages	4 000	7 400	4 152	--	7 883	1 600?	8 000	700?	1 000	?	?	?
Nb TCU 1990	--	5 300 000	3 608 000	--	--	--	560 000	--	--	--	--	--
WP necessary for **VW**	10 500	17 500	8 400?	700?(2)	4500 to 8000	1 720(2)	15 000	1 550(2)	3 200	27 000	1 000(2) to 1200	3 600 to 6100
WD necessary for **PW**	--	6 600	4 510	?	--	--	--	--	--	--	--	--
WP existing for **VW**	1 300	5 355	2 953	?	160	--	11 440	430	230	7 976	200?	2 252
Coverage **VW**	12 %	31 %	35 %	?	?	--	76 %	28 %	7 %	29 %	--	63 %
WP under construction or financed	1 000	4 314	1 000	?	2 678	--	1 595	400	--	150	100	2 351?
Total planned **WP** for **VW**	2 300	9 869	3 953	?	2 838	--	13 035	830	--	8 126	100?	4 603
Planned coverage **VW**	22 %	56 %	47 %	?	47 %	--	87 %	55.3 %	--	30 %	10 %	100 %
Nature existing PE												
. dug wells	500		x	x	1 870?		3 500	rares				834
. boreholes	1 900		x	x	160		9 000	430		8 000		248
. springs	--			x	3 672		--					1 170
. surface water	--				3 771		--					2 000
. wells in stream beds	--				493		--					
. qanats	--			x	--							

TCU Tropical Cattle Unit
VW Village-Water Supply
PW Pastoral-Water Supply
WP Water Point

(1) estimated at 75 % of total population
(2) one **WP** (Water Point) for 500 inhabitants
(3) renewal of old **WP**

Tableau 13a - State of aquifer exploitation and projected evaluation of water needs by 1990

Country	Guinea Equator.	Liberia	Mali	Mauritania	Niger	Nigeria	Sao Tome Principe	Senegal	Sierra Leone	Chad	Togo
Surface (km^2)	26 017	111 500	1 240 710	1 030 700	1 267 000	923 768	955	201 400	71 740	1 284 000	56 000
Population											
. total 1990	460 000	2 513 000	9 180 000	1 792 000	7 012 000	109 000 000	61 000(*)	7 012 000	3 500 000(?)	5 330 000	3 295 000
. rural 1990	345 000(1)	1 578 000	7 382 000	1 214 000	5 960 000	70 700 000	--	4 116 500	—	4 000 000	1 937 000
Nb villages	?	1 701	10 250	2 326	17 450	?	--	12 990	17 390?	13 695	2 570
Nb TCU 1990	--	--	4 070 000	5 092 000	7 541 000	--	--	4 680 000	--	10 540 000	--
WP necessary for VW	690(2)	6 300	47 000	5 570	19 900	141 400(2)	--	12 740	8 750?	>14 000	7 350
WD necessary for PW	--	--	28 000	6 365	8 520	--	--	5 850	--	10 000?	--
WP existing for VW	rares	1 592	6 830	1 550	9 070	26 600	--	1 534	370	2 200	2 240
Coverage VW	faible	25 %	19 %	27 %	45.5 %	5 %?	--	12 %	4 %	15.7 %	30 %
WP under construction or financed	?	2400?	4 775	1 930	2 330	80 to 300	--	1 127	300 to 1 700	100	1 770
Total planned WP for VW	?	4 000	11 605	3 480	11 400	26 800?	--	2 661	2 000?	2 300	4 010
Planned coverage VW	?	63 %	31 %	62 %	57 %	5 %?	--	21 %	23 %	16.5 %	54 %
Nature existing PE											
. dug wells		834				20 000	x		365	1 870	
. boreholes		641				6 600	x		x	316	
. springs		117					x		x		
. surface water		—				numerous	x				
. wells in stream beds						x					
. qanats											

TCU Tropical Cattle Unit
VW Village-Water Supply
PW Pastoral-Water Supply
WP Water Point

(1) estimated at 75 % of total population
(2) one WP (Water Point) for 500 inhabitants
(3) revewal of old WP

Table 13b - State of aquifer exploitation and projected evaluation of water needs by 1990

Country	Water needs (l/d/person)		Number of inhabitants/WP		Village size and suggested equipment			Remarks
	1985	1990	1 WP	Several WP's	<500hab.	500 to 2000 hab.	2000 to 5000 hab.	
Benin	10	20	500	500	manual	manual	manual	
Burkina Faso	10	25	500	400	manual	manual	manual	no village should be farther than 500 m from WP
Cameroon (north)	10	25	250	250	manual	manual	?	
Cape Verde Islands	10	25	?	?	manual?	?	?	
Central African Rep.(5)	10(?)	25	200	200(?)	manual	manual and PWS		maximum distance to WP = 1 km
Chad	15	20(?)	200	?	manual	?	?	
Congo	10	25	100/200	300?	manual			
Gabon	10	25	100/200	300?	manual	manual some solar pumps	PWS	
Gambia (the)	?	?	?	?	?	?	?	
Ghana	15	?	300	300	manual	?	?	distance WP/village = 300 m
Guinea Bissau	?	?	?	?	manual	?	?	
Guinea Conakry	10	20	600	100	springs manual	springs manual solar	?	distance WP/village <500 m
Guinea Equator.	?	?	?	?	?	?	?	
Ivory Coast	15	20 to 25	100 to 800	600?	manual	manual	PWS	
Liberia	20	25	250	250	springs manual	springs manual	?	
Mali	20	40	200	200	manual	solar or manual	PWS	
Mauritania	20?	40/25	200	200	manual	manual	PWS	25 l for nomadic population plus one WP as safety
Niger	10	20 to 25	600	250 to 300	manual	manual	PWS	
Nigeria	15(?)	25(4)	200	?	manual	motorized pumping	motorized pumping	115 l/h evaluated as water need in city
Sao Tome and Principe	?	?	?	?	?	?	?	
Senegal	12	40	500	500	manual or eolian	mecanized or solar	PWS	
Sierra Leone	10(?)	25(?)	100/300	300	springs manual	springs manual	?	
Togo	10	20	250	250	manual	manual	manual	

PWS Piped Water Supply network WP Water Point

Table 14 - National objectives and standards for rural water supply

II.3.3. National aims and standards chosen for the Village Water Supply projects

The water requirements imposed by the Village and Pastoral Water Supply can be described as four parameters : **quantity, quality, distance** to resource, **reliability** of the development.

II.3.3.1. Quantity of water necessary

The **quantity of water necessary** for the population's survival varies according to the country (table 14), but the minimum required lies between 7 and 10 l/day/head. The minimum basis adopted for emergency projects is 10 l/day/head. However, the present effective requirements are approximately 20 l/day/head, the most desired limit for 1990 being 25 l/day/head. This quantity suffices for drinking, cooking and washing (dishes and clothes).

While 20 to 25 l/day/head is the acknowledged medium-term aim, the demand for certain countries might be 40 l/day/head (Senegal, Mali, Mauritania), if it includes certain economic requirements such as market gardening, crafts, and small livestock. The average yield of the man-worked pumps means that up to 500 persons can use a water point. It is generally standard in development projects is one water point for 300 inhabitants, but demographic and morphologic constraints in certain regions may mean that a water point be installed for less than 200 people.

As for the consumption of a tropical cattle unit (TCU), it reaches 25 to 30 l/day. In wet zones, where abundant surface water and springs are found, the population is generally dispersed ; the cattle drink from ponds and the constructed water point is therefore reserved for human consumption only. In the arid regions, the cattle collects together around the water point and their needs enter into competition with those of the population.

II.3.3.2. Water quality

Unfortunately, the **water quality** in most cases is not subject to precise criteria. The descriptions used for defining water quality are still vague : only "safe" water is demanded with no reference to particular physical-chemical and bacteriological standards.

II.3.3.3. Distance between population and water point

The **distance of the resource** is becoming an increasingly important parameter. According to the existing resources (local hydrogeological environment) and the morphology, the distance between a village and the water point(s) may vary from a few metres to several kilometers. The population, however, desires, in most cases, to be able to have a water-point less than 500 m from the village, whenever the natural conditions permit.

II.3.3.4. Reliability of water supply

The **reliability** of the resource is expressed by the aquifer's reserve and its recharge, which will be mostly by rain water. As for the reliability of the water point actually functioning, this is expressed increasingly frequently by a request for a second equipped water point. The reliability of the resource will also allow to install powerful pumping systems on high-yield wells for the development of farming activities (small-scale village irrigation). As shown by recent examples from the Ivory Coast, this is an increasingly common development, especially where ageing catchment works need to be replaced.

II.3.4. Nature of the catchment works

In zones with high rainfall and marked relief, groundwater commonly issues from springs, which are tapped and developed mainly in the English-speaking countries but also in Guinea and Cape Verde. The water quality can be quite uneven but the creation of latrines simultaneously with that of the water points tends to improve the quality of the spring water.

The present trend tends to favour the drilling of boreholes so as to satisfy criteria of resource quality and longevity. Well drilling usually is a rapid process and enables relatively deep resources to be tapped. The "down-the-hole-hammer" drilling technique can locally reduce the distance between a village and a water point for it can easily penetrate the hard rock and gain access to the resource.

On the other hand, the difficulty of maintening such boreholes is a real constraint in certain areas and must be taken into consideration. In some, as yet little developed, regions the villagers are presently unable to ensure such maintenance (not in the least because of the unavailability of spare parts) and have the understandable desire to have a well to ensure their survival. Such wells, even though they are more in agreement with the desires expressed by the rural population, nevertheless supply water of generally poor sanitary quality ; moreover, they take long to sink especially in areas of hard rock, and are not always well adapted to the hydrogeological environments of the West African basement. Finally they are usually more expensive than a borehole fitted with a manual pump.

Boreholes exist in many varieties, which depend on geographical location and geological conditions. For instance, wells drilled in the "basement" show certain similarities in their geometrical characteristics and their equipment. They are usually between 30 and 80 m deep (45 to 50 m average). High yields (5 to 10 m^3/h, exceptionally even more) may be reached, but in most cases the water supply is limited by manual pumping (0.5 to 2 m^3/h) depending on the depth of the water table.

On the other hand, several types of borehole construction can be distinguished in discontinuous environments. Differing designs of drilling and equipment specifications are given in figures 3 and 4, depending on whether the basement, the weathered zone or both together are to be tapped.

In the French-speaking countries, boreholes that intend to exploit the discontinuous-type of aquifers, penetrate the hard fissured rock for 10 to 30 m ; the section in bed rock may be cased or not, but the upper, weathered, part will always be cased (in a larger diameter). Certain boreholes are drilled and cased in the same diameter throughout. In the English-speaking countries, where percussion drilling is the prevalent technique, the boreholes stop traditionally at the hard rock (Ghana, Nigeria), especially when the weathered rock is very thick.

In the area being studied, drilling diameters vary from 4" to $10^{5/8}$", the most common being between 6" and 8". The casing tubes traditionally used are of PVC and 4" to 6" diameter, the most used sizes being the 125/140 mm or 110/125 mm classes. These diameters allow the installation of one or two manual pumps.

Above the generalized aquifers, the minimum borehole depth is around 30 m, but can be several hundred metres. These medium-depth boreholes may have the same diameter throughout or varying diameters, depending on the nature of the formations intersected. They are, in most cases, drilled by rotary method with mud, in one diameter only ($8^{1/2}$" to $9^{7/8}$") cased in PVC of 120/140 mm diameter, and screened at the aquifer level by multiple lengths of 5.80 m slotted casing. The deep boreholes are usually more complex and their equipment may be monolithic (casing and screens are in one piece) or

Village-type boreholes in crystalline basement.
Typical hole sections of wells drilled by rotary down-the-hole-hammer technique

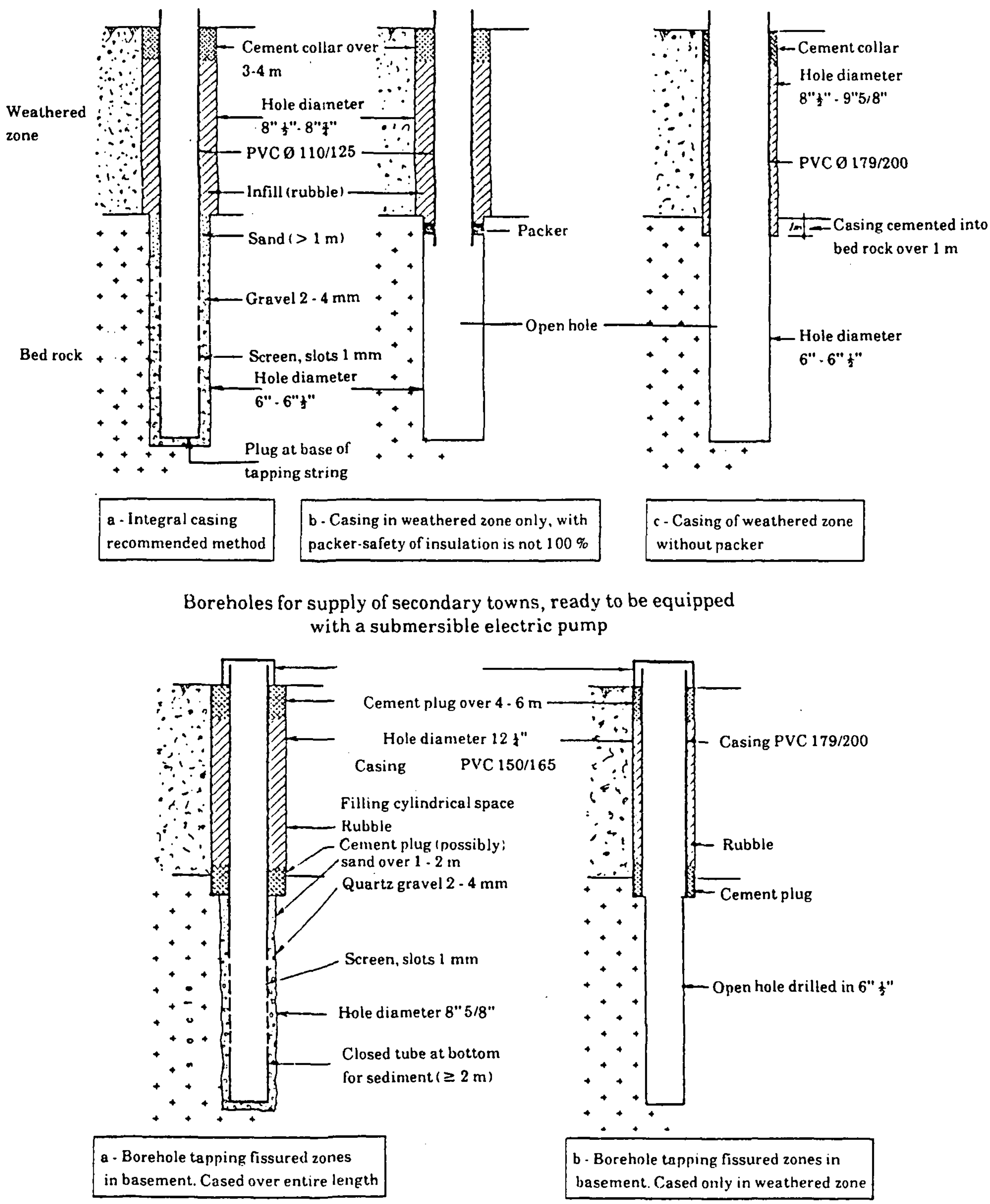

Figure 3 - Types of boreholes in crystalline-basement areas

After: "Hydrogeological evaluation of water-supply projects in crystalline-rock areas of the West African shield".- ICHS-BGR, February 1985

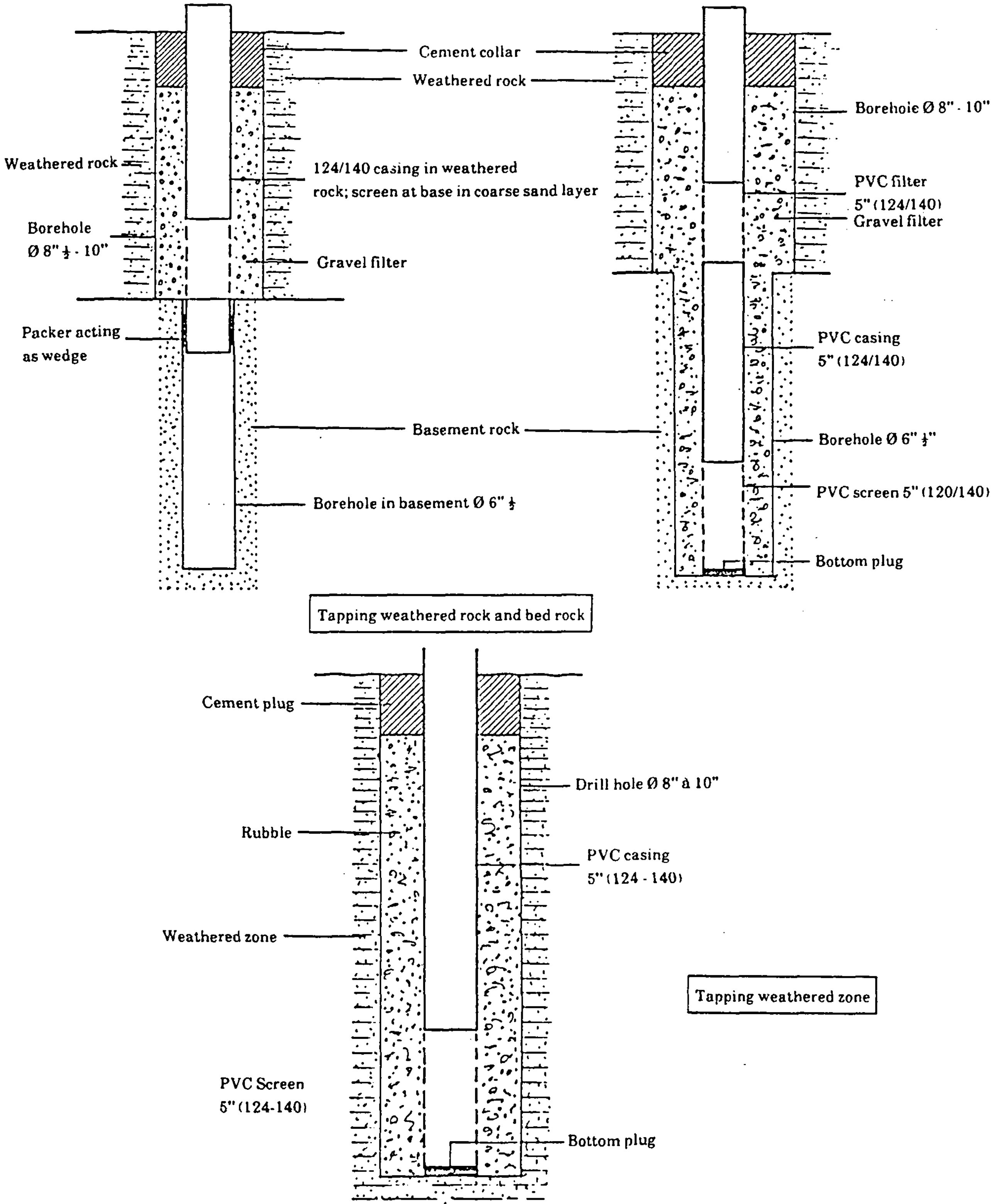

Figure 4 - Types of wells in fissured bed-rock and below weathering zone. Village-type of boreholes in crystalline basement drilled by rotary/ down-the-hole-hammer methods

After:"Hydrogeological evaluation of water-supply projects in crystalline-rock areas of the West African shield" .- ICHS-BGR, February 1985 telescopic (the tapping string is separate from the tubes making up the pumping chamber).

The construction of the wells calls upon techniques that vary greatly : drilled, or dug by hand, with or without mechanical assistance. Their technical characteristics are equally varied, such as wells with bare walls, faced with bricks or rubble stone, tubbed, concreted, with or without bottom plates, with or without gravel-packs, and their diameters may be single or telescopic, varying from 0.80 m to more than 4 m, the most common being between 1.60 m and 2 m. The depth of dug wells can be as much as 100 m, but normally is not much more than 15-25 m in (altered) bed rock. Even in periods of low groundwater, the water column in the wells must be around 7 to 10 m for the well to be perennial. It is common to come across certain wells completed by an inside borehole (the borehole dug-well couple) or by a borehole next to it, outside (the borehole counter-well).

II.3.5. Cost of catchment works

The cost of catchment works was evaluated with the help of the accessibility descriptor (see inset map and I.1.2.1.) by comparing the success probability with the depth actually drilled. Access to the resource (depth of the groundwater) usually does not pose special difficulties, except for hilly areas (Benin, Togo, Ghana, Guinea Conakry), certain regions with discontinuous aquifers (such as the "basement" of Gabon) and the axis of the Mauritanian Mountains.

In terms of cost, it is usually difficult to give an average figure for a borehole due to the nature of the project (boreholes drilled by the state or by a private firm), the size of the project, the difficulties of access and supply, the total depth and diameters, the type of the borehole equipment and, finally, because of competition.

Besides the above, the expenses for ancillary studies, equipment, pumping material and cost of educating the population in water problems are not always clearly given. Finally, actualisation of costs by each country is uncertain. The costs of the main works, given in table 15, are for all works without distinguishing whether they were positive or without success, by simply dividing the total cost of the standard project (inclusive of the cost of technical assistance and accompanying measures, inquiry, instruction and encouragement, training, which vary according to the project) by the total number of works.

Type of Water Point	Cost range in Ecu's*			Remarks - Average cost of successful Water Point
Boreholes in basement terrain	5,000	to	24,000	7,500 à 12,000 Ecu in general
Dug wells	1,800	to	24,000	Variable cost : for 40 m depth = 15,000 Ecu
Spring development	1,500	to	5,000	2,500 Ecu on average
Boreholes in sedimentary terrain	10,000	to	22,000	Water Point < 100 m fitted with PVC casing Ø 4 à 8" = 12 500 Ecu on average
	12,000	to	500,000	Deep boreholes of 200 to 700 m, steel casing Ø 8"

* 1 Ecu = 342 F CFA = 6,84 FF (May, 1986)

Table 15 - Typical costs for major types of water points

For the main components of a project the following financial elements can be distinguished (table 16) :

Project Components	Financial impact on total project cost (%)			Remarks
Boreholes	59	to	75	66 on average
Study and Checking	10	to	18	15 on average
Pumping equipment	10	to	14,5	12 on average
Educational	approximately 7			
Activities	0	to	3	

Table 16 - Financial impact of project components on total cost of village-water-supply project

II.3.6. Cost of making water available and average cost of a m³ of water

Calculating the cost of water earmarked for supplying a village, in fact is the same as assessing the cost of the energy needed for lifting the resource to the surface.

This exploitation-cost notion was described in I.1.2.2. and shown on the map entitled **Exploitability descriptor** (in pocket). It is similar to the price of a m^3/h installed, compared to the investment cost required to construct the borehole.

Apart from the areas with low potential (II.3.1.) which are essentially found in the Sahel region, and those with poor and uneconomic development possibilities, the exploitation conditions of the groundwater resource prove to be satisfactory as a whole over more than two thirds of the map area. This leads to the range of costs for making the water available as shown in table 17, it being understood that the costs given were calculated during recent village water supply programmes, in basement as well as sedimentary zones.

Delivery cost of m^3/h	Bottom cost Ecu	Top cost Ecu	Average cost Ecu
Unequipped borehole	2 075	3 582	2 705
Fully equipped borehole	12 580	22 295	14 650
Fully equipped borehole integrated in distribution network	16 300	52 017	35 272

Table 17 - Cost of m^3/h water at the three main stages towards the consumer

Nevertheless, the most common notation of cost of a cubic metre of water refers to the utilization cost for as long as the catchment work and its equipment last. In basement areas (discontinuous aquifer) the average cost of a m^3 of water varies from 0.18 to 0.34 Ecu, taking into consideration :

1. amortization of the work :

$$\frac{\text{Cost of the work}}{\text{15 years}} = \frac{\text{7,310 to 11,696 Ecu}}{\text{15 years}}$$

2. amortization of the pumping installation :

$$\frac{\text{Cost of pump}}{\text{5 years}} = \frac{\text{1,462 Ecu}}{5}$$

3. maintenance costs for well and pump : 175 Ecu/year

4. the average annual pumped volume which is 3,650 m^3 for Village Water Supply.

Should the scope of Village Water Supply be widened, according to the pumping and supply means adapted to the exploitable yield and to the population to be served (manual pump, electrical pump connected to the national grid or supplied by an electric generator, photo-voltaïc solar pump, vertical-axis pump with diesel engine) the average cost of a m^3 may be from 0.19 to 0.31 Ecu.

II.3.7. Exploration methods

Inside the great sedimentary basins with generalized aquifers, the exploration for water resources no longer poses special problems on a small scale, especially since the on drafting, at the initiative of ICHS, of groundwater-resource planning maps as well as maps showing the water's aptitude for irrigation. In areas with discontinuous aquifers, however, exploration can be difficult because of the inherently limited geographical extent of the ressource.

The scope of the present document does not allow a detailed description of the great variety of surface exploration methods used to explore such aquifers, but references on this subject can be found in the extensive technical literature devoted to these problems, and, in particular, to that published by the ICHS and by BRGM.

It is probably true that surface-geophysical prospecting methods are the best approach for locating groundwater in discontinuous shallow environments, as was demonstrated time and again in the "village water supply" projects during the last decade, especially when combined with classic photo-interpretation. Among the most widely used and successful surface-geophysical prospecting methods are electrical methods, such as electrical sounding, and simple or combined electrical resistivity. However, it should be remembered that the interpretation of an electrical signal holds no guarantee that a water resource is actually present, nor that it has a certain size. The fact that the resource is generally vertically below conductive zones has only a **probabilistic character.**

Electromagnetic exploration methods are better understood when comparing a subsurface discontinuity and the electromagnetic disturbance caused by it. Paradoxically, they are not much used, probably due to the poor availability of the electromagnetic waves sent out by the transmitter installations in operation. As for magnetic methods, they are not used very much any more. This is difficult to understand, especially as their maximum efficiency is above formations with a high magnetic susceptibility (greenstone, dolerite, basic to ultra-basic rocks), which occupy a significant area of the West African shield.

Seismic methods are mentioned only for completeness sake, as their operational cost is much more than could be borne by the typical financing granted to a village or hydro-agricultural type of development project. They are, all the same, very efficaceous and well adapted to the problem posed here.

Type of catchment work	Characteristics	Depth (m)	Casing Ø (mm)	Suggested type of construction	Construction and/or Exploitation constraints
Village-type borehole in fissured bed-rock	Very short completion time only type of catchment work that can reach the fracture zone in hard rock	40 to 80	110/125 or 125/140	Percussion rig, or mixed rotary/percussion rig	Respect quality standards for equipment. Select PVC casing specially adapted to drilling, which can accept proper gravel/rubble packing. Isolate weathered zone by integral casing/gravel pack or the use of a packer, whose tightness should be checked
Village-type borehole in weathered zone (rarely executed)	Short completion time if weathered zone does not collapse	60	125/140	Rotary drilling with mud	Plan for temporary casing of loose material, which should be drilled in Ø 12 1/4"
Water-supply boreholes for small towns in fissured bed-rock	Very short completion time	80	150/165 or 179/200	Percussion rig or mixed rotary/percussion rig	Borehole to be equipped with 4" submersible electric pump. Respect annular-space standards. Larger casing diameter can accept 6" pumps
Hand-dug well (crystalline or sedimentary bed-rock)	Shaft-sinking possible but very expensive in hard rock. Slow to complete	20 to 40	1400/ 1800	Compressors jack hammers explosives specialized well diggers	Difficult to tap properly a hard rock / (basement or massive limestone). Maximum depth of static water level is 70 m
Drilled well (with bucket anger)	Short completion time, but only for soft ground without hard layers	27	1000	Bucket-anger drill rig	Diameter restricts exploitation to two or three ropes. Needs transportation of tube segments when they are concrete.
Well dug with a mechanical shovel	Good in alternating soft and hard ground. Rather long completion time	50	1000	Mechanical shovel	Follow the pilot-studies carried out in Niger. Well diameter does not allow use for herds. Wells tend to collapse during digging ; subject to transport of concrete well tubes. Such wells can be dug in weathered rock, when conditions are favourable.

Table 18 - Main development characteristics based on well types

Generally, and this is backed up by field experience, it is the combination of several methods that gives the best possible result in exploration for water, and not the use of one method on its own.

II.3.8. Guide for the choice of type of catchment work

The following hydrogeological factors govern the choice of a groundwater catchment work :

- the rock type(s) of the layer(s) to be intersected ;
- the water-bearing properties of the formations (useful porosity, degrees of fissuring and fracturing) ;
- the depth of the groundwater surface ;
- the predictable depth of the water level at rest in the work, once constructed ;
- possible or desired extraction yield.

Other factors intervene, depending on the construction means and methods available in a country, on the maintenance possibilities (technological cost of pumping) and, above all, on the planned use (domestic, pastoral, industrial needs).

Depending on these different factors, which are not everywhere equally well-known over the whole mapped area, a guide for choosing catchment work types may be proposed, while trying to respect the desires expressed by the local population. Table 18 presents the main development tendencies according to the type of construction recommended. For more details, see II.3.4.

Part III

USE OF SYNTHESIS MAP AND

FURTHER DEVELOPMENT OF MAPPING

III.1. WAYS OF USING THE MAP

The synthesis map, designed to assist making development decisions and presented at a scale of 1:5,000,000 is based on three interactive descriptors. The progress made in the quality of information restitution proves to be undeniably important as the mapped data can be accessible by the independent restitution of each factor at the level of each "intermediate" map based on one of the three descriptors (3 maps inset).

The user can, in this way, make sure that a zone with an overall satisfactory groundwater potential does not hide a high failure rate or that the water levels are very deep, for example as the user can alter the weighting of the descriptor-factors. The decision maker or planner will thus read the map by justaposing the three descriptive maps, in order to quantify as exactly as possible the variability of the classes characterizing the zone chosen for study.

At a second stage, it will be easy to determine the variability thresholds of each factor, especially in view of the fact that the authors have tried to give a maximum of information on most of the zones.

* *
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III.2. FURTHER DEVELOPMENT OF MAPPING

The further development of this type of mapping will mean a continued effort in increasingly sophisticated data acquisition and processing, which is of paramount importance for the mapping to be of assistance in development decisions at national or international level.

III.2.1. Optimization of data collecting and acquisition

The collection and acquisition of data must hinge on a restricted but not restrictive list of the variables as well as any systematic observations made during execution of the work programmes.

This could result in drafting a data-collection check list per borehole, which could be applied to all the future water-supply programmes. The "specifications and recommendations for data collection" are appended as a separate document.

After collating the data, they may be entered into a computer memory, care being taken to attribute the data with an "information quality" coefficient based on their representativity, on the programme-execution conditions and, lastly, on the geographical and technical characteristics of the works. These instructions, described in the "Specifications, etc", will form the basis for all future maps.

III.2.2. Harmonized information processing

The statistical data processing must only be applied to homogeneous populations with reliable accuracy. Representative statistical parameters should be selected as well, including :

- the **average and its standard deviation,** a parameter that defines standard profiles and their spatial variability, and integrates the extreme values of the data, which possibly reflect exceptional events that should not be ignored ;
- the **median,** defining the values that will be most probably encountered ;
- the **probabilities of excess,** necessarily associated with the calculations of the confidence intervals that indicate the weighting of the results according to the absolute frequency of the processed sample.

III.2.3. Creating and optimizing integrated software

The present computer-assisted mapping is the end product of a data-restitution process with many different parts, consisting in data acquisition, processing and restitution, all of which call upon different methodologies, as a result of the heterogeneity of both the available information and its presentation. These can take the form of :

- **manual use of the files** referring to the different development projects, only part of which were subjected to computerized data acquisition and to statistical analyses ;
- **manual preparation** of information-exploiting statements from the retained parameters ;
- **traditional map draughting** ;
- **acquisition,** on a graphic computer terminal, of all the information previously mapped, to render the process **variable and revisable on request.**

In the future, integrated computer-assisted programmes, aiding in data acquisition to map making will depend on **a coordinated use of a coherent computerized system** :

- **data acquisition,** elementary statistical processing, drafting of exploitation statements based on software like the HIVI programme, which runs on **Hewlett-Packard** equipment ;
- **interfacing and statistical processing** on a VAX 780 main-frame computer by FIESTA software ; publication of elementary equal-value contour maps (LUCAS, UNIRAS, and INGRID programmes) ;
- **automatization of the combinational calculations** using the data-processing bases, by specialized software (SYNERGIE) that allows any combinational synthesis (assistance in decision making) ;
- **transfer into infographic memory** and automatic tracing of outlines (computer-assisted mapping) ;
- **management of the graphic data** base by using graphic computerized equipment, such as INTERGRAPH IGB/DMRS ;
- **unlimited reproduction** of the image on an automatic plotting table AVIOTAB WILD.

III.3. EXAMPLE OF THE POSSIBILITIES OF COMPUTER-ASSISTED MAP PUBLICATION (fig. 5 to 8)

In order to illustrate the recommended approach to mapping by country or by region, a series of maps is presented here, covering the territories of Ghana, Togo and Benin. These maps show the different preparation stages leading up to a final synthesis document, from the maps of equal-factor values (monothematic map of depth, productivity, etc.) to maps of descriptors (combination of 2 factors) and then to the map of the results of combining the 3 descriptors : **accessibility, exploitability,** and **reliability.**

Finally, as a demonstration of the decision-making possibilities, a sample map is shown that is a result of new and different choices of threshold for each parameter.

All the cases presented here give an idea of the operational versatility of this kind of mapping, which makes it possible to visualize an appropriate answer to a specific user need, as long as the basic data are homogeneous and reliable.

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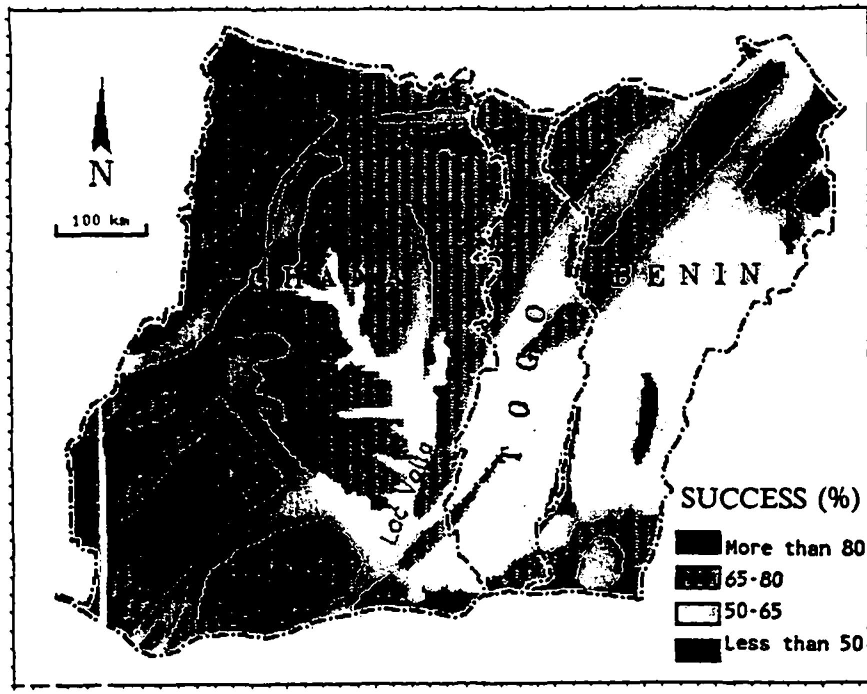
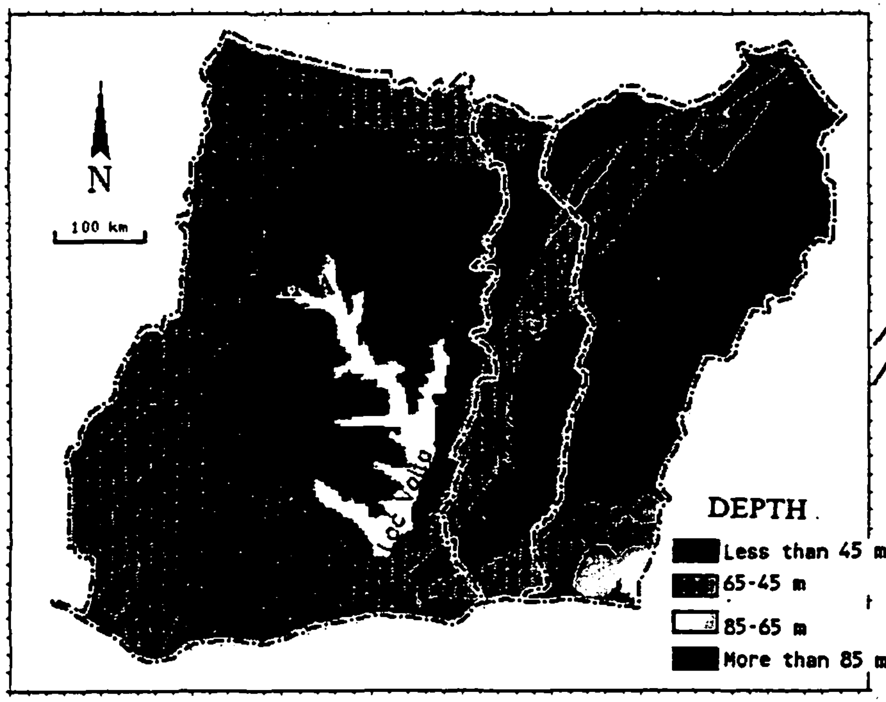
Computer-assisted mapping for use in decision making

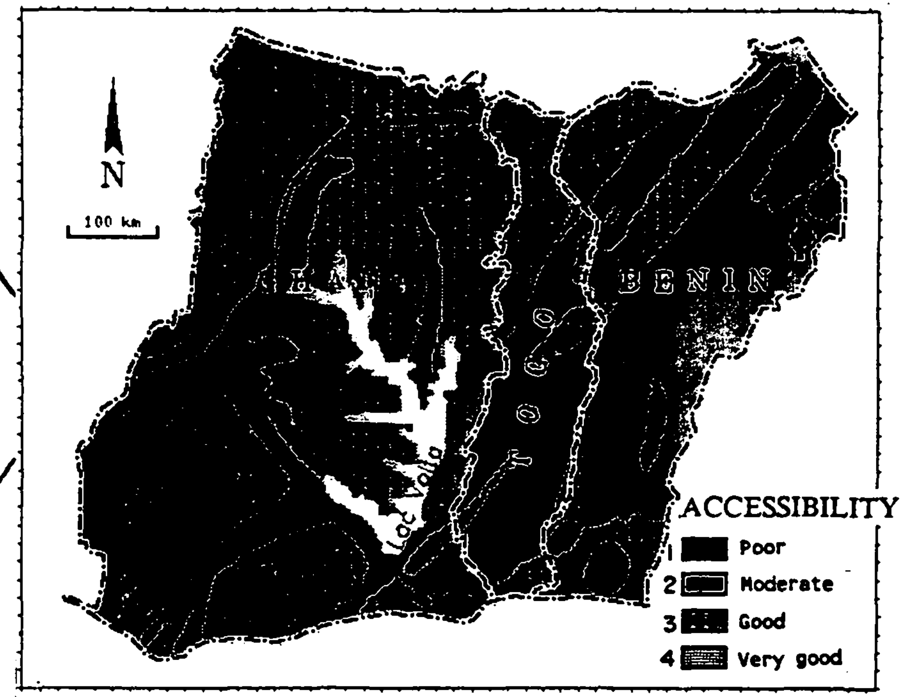
ACCESSIBILITY DESCRIPTOR



Success probability factor



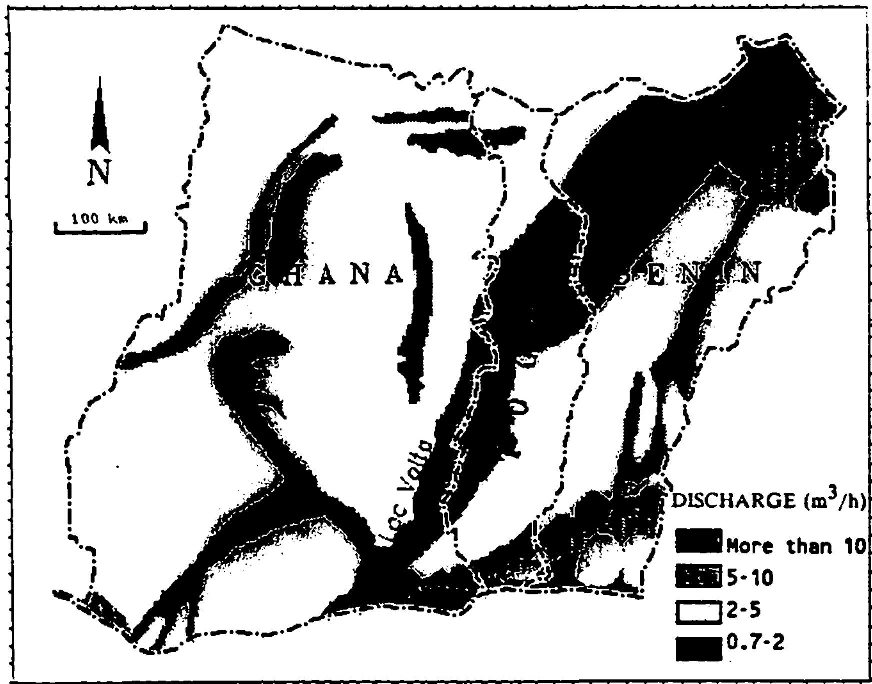
Borehole-depth probability factor



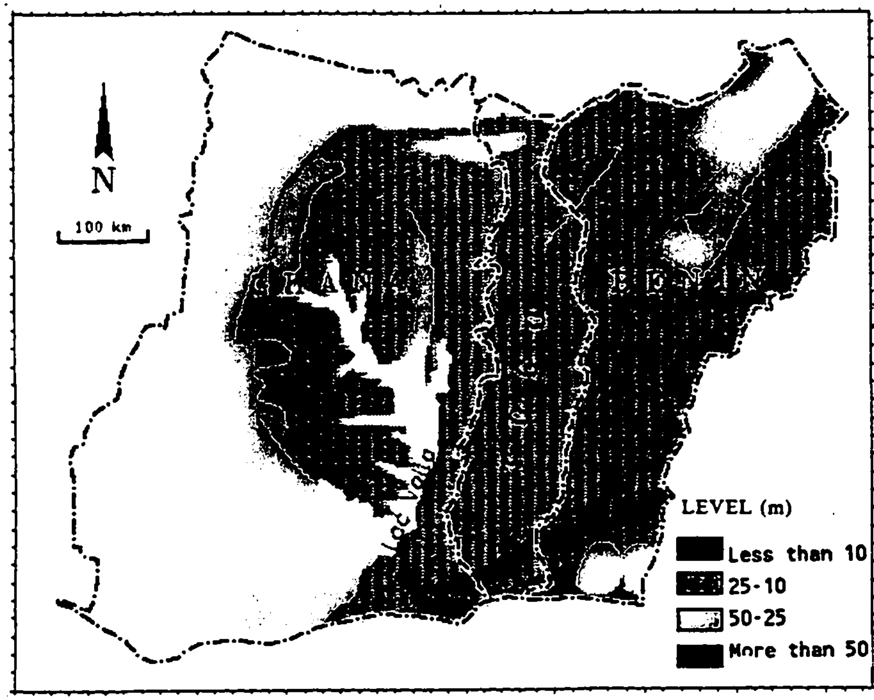
Category 1:	Zone of high-risk and/or costly water capture
Category 2:	Zone of average-risk and/or costly water capture
Category 3:	Zone suitable for shallow boreholes with an average success probability
Category 4:	Zone suitable for shallow boreholes with a high success probability

Figure 5 - Computer-assisted mapping for use in decision making: Accessibility Descriptor

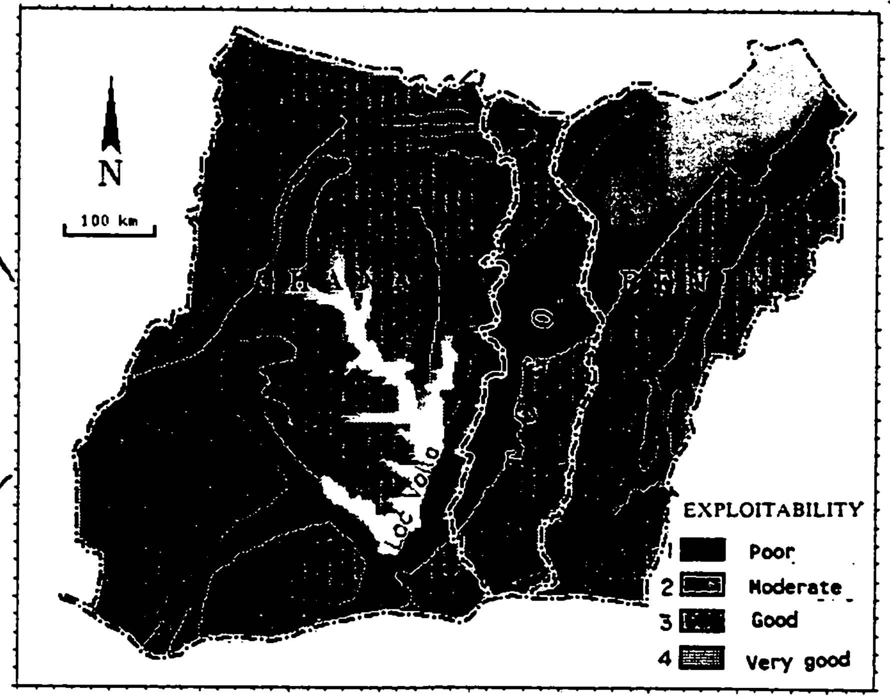
EXPLOITABILITY DESCRIPTOR



Productivity or discharge factor



Extraction or tapping-depth factor

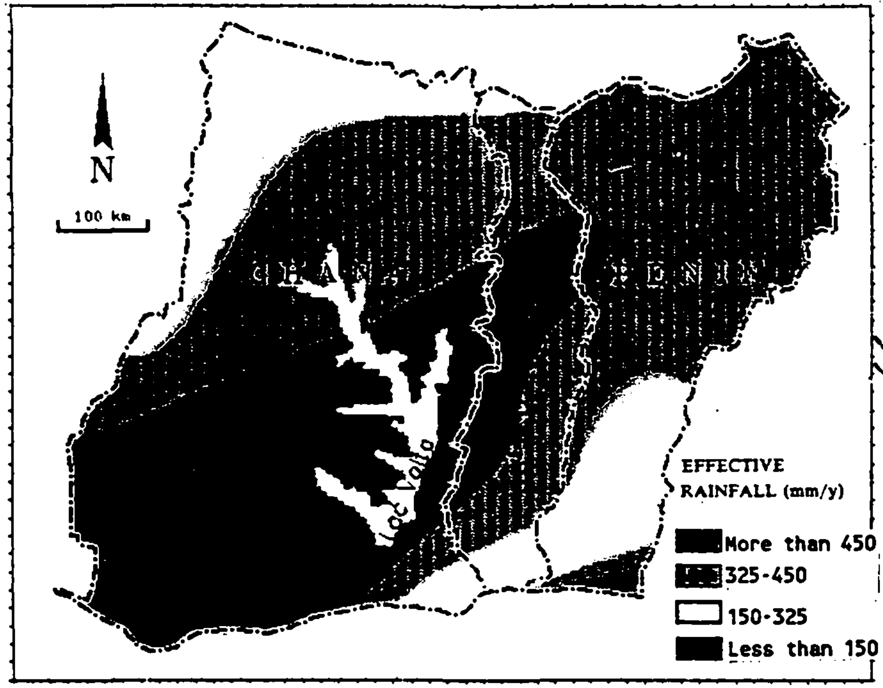


Category 1	Survival threshold
Category 2	Area favourable for village water projects designed to provide drinking water
Category 3	Area favourable for small-scale irrigation and for drinking water for regional centres
Category 4	Area favourable for urban water supply and mechanized agriculture

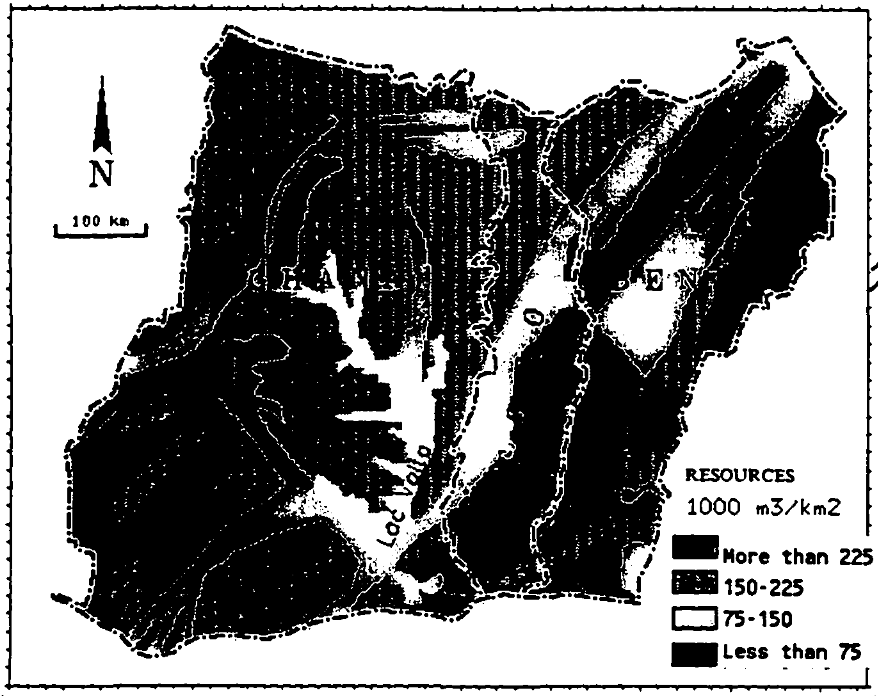
Figure 6 - Computed-assisted mapping for use in decision making: Exploitability Descriptor

Computer-assisted mapping for use in decision making

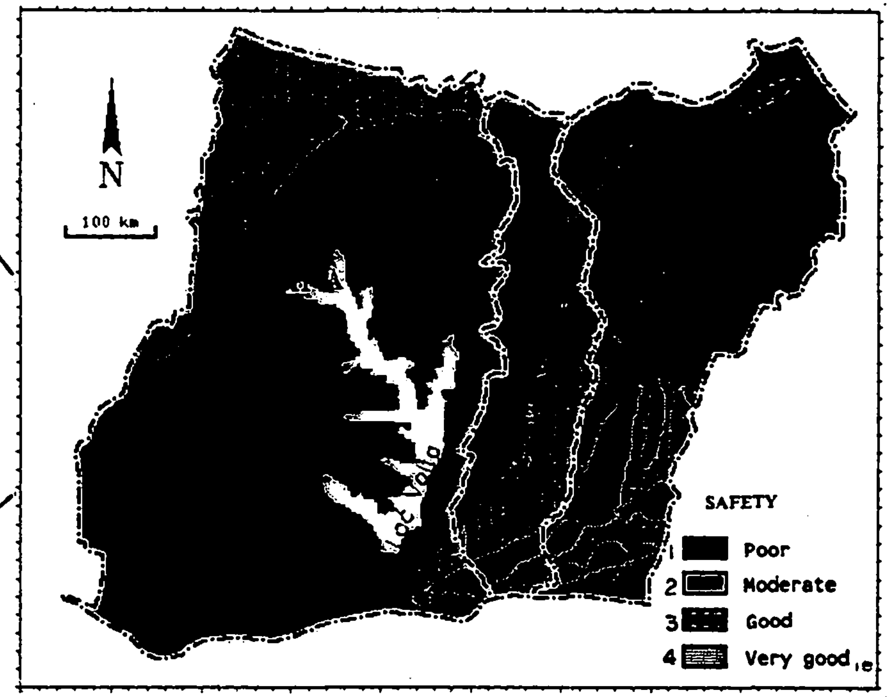
RELIABILITY DESCRIPTOR



Mean annual effective rainfall factor (resplenishment index)



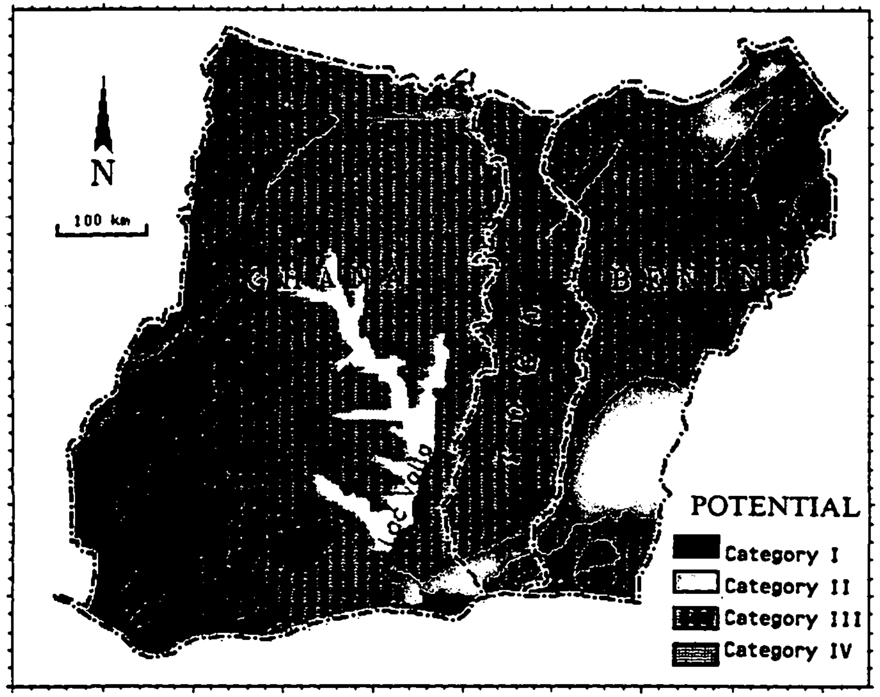
Aquifer resources factor



Category 1	Zone with precarious resources
Category 2	Zone with resources vulnerable to drought
Category 3	Zone with modest resources, variably vulnerable to drought
Category 4	Zone with substantial resources, relatively invulnerable to drought

Figure 7 - Computer-assisted mapping for use in decision making: Reliability Descriptor

MAP OF POTENTIAL GROUNDWATER RESOURCES



Categorical synthesis combining three descriptors: accessibility, exploitability, and safety

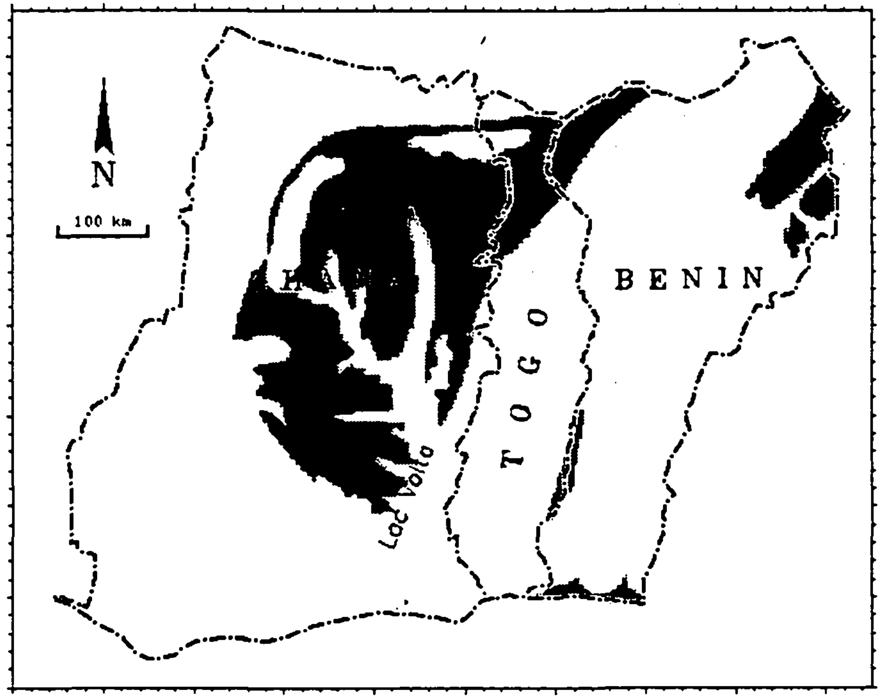
Category I: Unfavourable terrain, limited to exploration for drinking water in identified structures

Category II: Relatively-unfavourable terrain typified by barely-economic potential and a high risk of failure

Category III: Favourable terrain, with advantageous development potential and a moderate degree of risk

Category IV: Very favourable terrain typified by extensive development potential with good economic return and minimum risk

EXAMPLE OF SELECTION OF ZONES SATISFYING CRITERIA SPECIFIED ON THE BASIS OF A DEVELOPMENT TARGET



Criteria identifed:

Rate of success between 65 and 85%
Borehole depth between 45 and 65 m
Discharge sought between 2 and 5 m^3/h
Total pressure head between 10 and 25 m
Mean annual effective rainfall between 325 and 450 m
Local aquifer resources between 150,000 and 225,000 m^3/km^2

Figure 8 - Map of Potential Groundwater Resources. Example of selection of zones satisfying criteria specified on the basis of a development target

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REFERENCES

Abbreviations used in the following list of references

AAGS	Association of African Geological Surveys
BRGM	Bureau de Recherches Géologiques et Minières
CEC	Commisison of the European Communities
DFMG	Federal Directorate of Mines and Geology
DGM	Directorate of Geology and Mines
EDF	European Development Fund
ICHS	Inter-African Committee for Hydraulic Studies
IGN	Institut Géographique National (France)
LCHF	Laboratoire Central d'Hydraulique de France
OBEMINES	Benin Bureau of Mines
SODEMI	Mining Development Company of the Ivory Coast
UNDP	United Nations Development Program

N.B. Notwithstanding the English titles of the following references, many of the actual publications are in French.

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sheet 8 : Bangui - Riyadh
sheet 10 : Brazzaville - Réunion

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Appendix

CALCULATION OF MEAN EFFECTIVE RAINFALL

Stations	Location		Interannual average by month												Total yearly average
	Long.	Lat.	J	F	M	A	M	J	J	A	S	O	N	D	
NIORO DU S	-9.60	15.23	0.	0.	0.	0.	0.	0.	4.	29.	8.	0.	0.	0	41
SAN	-4.90	13.28	0.	0.	0.	1.	0.	0.	3.	54.	34.	2.	0.	0.	94.
SEGOU	-6.15	13.40	0.	0.	0.	0.	0.	0.	7.	57.	28.	1.	0.	0.	93.
SIKASSO	-5.68	11.35	0.	0.	0.	0.	2.	1.	75.	196.	95.	15.	0.	0.	384.
TESSALIT	0.98	20.20	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOMBOUCTOU	-3.00	16.72	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NOUAKCHOTT	-15.95	18.10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
AIOUN	-9.60	16.70	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
AKJOUJT	-14.37	19.75	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ATAR	-13.07	20.52	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BOUTILIMIT	-14.68	17.53	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
F'DERICK	-12.70	22.68	0.	0.	0.	0.	0.	0.	0.	0.	1.	0.	0.	0.	1.
KIFFA	-11.40	16.63	0.	0.	0.	0.	0.	0.	0.	1.	7.	0.	0.	0.	8.
NEMA	-7.27	16.60	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NOUADHIBOU	-17.03	20.93	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ROSSO	-15.82	16.50	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TIDJIKJA	-11.43	18.57	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NIAMEY AER	2.17	13.48	0.	0.	0.	0.	0.	0.	6.	35.	19.	0.	0.	0.	60.
AGADEZ	7.99	17.00	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BILMA	12.92	18.68	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BIRNI N KO	5.26	13.80	0.	0.	0.	0.	0.	0.	5.	21.	10.	0.	0.	0.	36.
GAYA	3.50	11.98	0.	0.	0.	0.	0.	4.	19.	86.	51.	1.	0.	0.	161.
MAINE SORO	12.02	13.22	0.	0.	0.	0.	0.	0.	0.	34.	2.	0.	0.	0.	36.
MARADI	7.42	13.47	0.	0.	0.	0.	0.	0.	7.	41.	13.	0.	0.	0.	61.
N GUIGMI	13.12	14.25	0.	0.	0.	0.	0.	0.	0.	13.	0.	0.	0.	0.	13.
TAHOUA	5.30	14.90	0.	0.	0.	0.	0.	0.	2.	8.	1.	0.	0.	0.	11.
TILLABERY	1.45	14.20	0.	0.	0.	0.	0.	0.	0.	21.	4.	0.	0.	0.	25.
ZINDER	8.98	13.80	0.	0.	0.	0.	0.	0.	1.	31.	0.	0.	0.	0.	32.
DAKAR-YOFF	-17.50	14.73	0.	0.	0.	0.	0.	0.	4.	35.	40.	9.	0.	0	88.
DIOURBEL	-16.23	14.65	0.	0.	0.	0.	0.	0.	5.	40.	52.	5.	0.	0.	102.
KAOLACK	-16.07	14.13	0.	0.	0.	0.	0.	0.	11.	56.	54.	6.	0.	0.	127.
KEDOUGOU	-12.22	12.57	0.	0.	0.	0.	0.	6.	106.	201.	189.	63.	0.	0.	565.
KOLDA	-14.97	12.88	0.	0.	0.	0.	0.	2.	75.	196.	174.	45.	0.	0.	492.
LINGUERE	-15.12	15.38	0.	0.	0.	0.	0.	0.	3.	13.	15.	5.	0.	0.	36.
MATAM	-13.25	15.63	0.	0.	0.	0.	0.	0.	0.	4.	13.	2.	0.	0.	19.
PODOR	-14.93	16.63	0.	0.	0.	0.	0.	0.	0.	2.	1.	0.	0.	0.	3.
SAINT LOUI	-16.45	16.05	0.	0.	0.	0.	0.	0.	1.	6.	4.	4.	0.	0.	15.
TAMBACOUND	-13.68	13.77	0.	0.	0.	0.	0.	0.	31.	124.	81.	14.	0.	0.	250.
ZIGUINCHOR	-16.27	12.55	0.	0.	0.	0.	0.	1.	139.	348.	211.	41.	0.	0.	740.
N'DJAMENA	15.03	12.13	0.	0.	0.	0.	0.	0.	8.	56.	13.	0.	0.	0.	77.
ABECHE	20.85	13.85	0.	0.	0.	0.	0.	0.	4.	29.	7.	0.	0.	0.	40.
AM TIMAN M	20.28	11.03	0.	0.	0.	0.	0.	1.	34.	141.	32.	0.	0.	0.	209.
ATI	18.33	13.22	0.	0.	0.	0.	0.	0.	6.	29.	2.	0.	0.	0.	37.
BOL BERIM	14.72	13.47	0.	0.	0.	0.	0.	0.	1.	15.	0.	0.	0.	0.	16.
BOUSSO MET	16.72	10.48	0.	0.	0.	0.	0.	1.	32.	133.	54.	2.	0.	0.	222.
FAYA LARGE	19.17	18.00	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SARH METEO	18.38	9.13	0.	0.	0.	0.	0.	3.	69.	151.	75.	4.	0.	0.	302.
MONGO	18.68	12.18	0.	0.	0.	0.	0.	0.	18.	138.	22.	0.	0.	0.	178.
MOUNDOU ME	16.08	8.57	0.	0.	0.	0.	0.	6.	93.	193.	107.	10.	0.	0.	410.
PALA METEO	14.97	9.37	0.	0.	0.	0.	0.	6.	56.	127.	77.	5.	0.	0.	271.
LOME AERO	1.25	6.17	0.	1.	0.	6.	19.	141.	52.	7.	2.	2.	0.	0.	230.
OTURKPO	8.10	7.20	0.	0.	0.	0.	0.	0.	7.	61.	143.	59.	0.	0.	270.
WUKARI	9.80	7.90	0.	0.	0.	0.	0.	0.	0.	0.	117.	33.	0.	0.	150.
ISANLU MAK	5.80	8.20	0.	0.	0.	0.	0.	16.	123.	87.	135.	2.	0.	0.	363.
RIYOM	8.80	9.60	0.	0.	0.	0.	0.	0.	80.	170.	78.	0.	0.	0.	328.
KONTAGORA	5.50	10.4	0.	0.	0.	0.	0.	0.	0.	114.	133.	0.	0.	0.	247.
KUDARU	8.45	10.6	0.	0.	0.	0.	0.	0.	79.	197.	121.	0.	0.	0.	397.
BAUCHI	9.80	10.3	0.	0.	0.	0.	0.	0.	36.	240.	55.	0.	0.	0.	331.
BIU	12.2	10.6	0.	0.	0.	0.	0.	0.	14.	146.	114.	0.	0.	0.	274.
ZURU	5.20	11.4	0.	0.	0.	0.	0.	0.	0.	180.	145.	0.	0.	0.	325.
KANO	8.50	12.0	0.	0.	0.	0.	0.	0.	5.	213.	17.	0.	0.	0.	235.

Stations	Location		Interannual average by month												Total yearly average
	Long.	Lat.	J	F	M	A	M	J	J	A	S	O	N	D	
BAFIA	11.23	4.73	0.	0.	10.	27.	40.	22.	39.	53.	130.	191.	29.	0.	541.
BANYO	11.82	6.75	0.	0.	2.	24.	54.	77.	200.	166.	181.	105.	4.	0.	813.
MEIGANGA	14.28	6.53	0.	0.	0.	1.	6.	42.	154.	170.	153.	60.	1.	0.	587.
YAOUNDE (A	11.53	3.84	0.	0.	13.	53.	94.	76.	14.	13.	127.	193.	54.	0.	637.
YOKO	12.30	5.53	0.	0.	0.	3.	24.	60.	101.	106.	225.	208.	26.	0.	753.
ALINDAO (M	21.20	5.05	0.	0.	1.	1.	21.	27.	65.	135.	107.	89.	24.	0.	470.
BAMBARI (A	20.67	5.77	0.	0.	3.	3.	16.	33.	65.	111.	118.	94.	4.	0.	452.
BANGASSOU	22.83	4.73	0.	0.	0.	10.	54.	61.	65.	90.	79.	124.	19.	0.	502.
BIRAO (MET	22.78	10.28	0.	0.	0.	0.	2.	0.	26.	64.	36.	1.	0.	0.	129.
BOSSEMBELE	17.65	5.27	0.	0.	0.	0.	6.	48.	96.	155.	150.	90.	10.	0.	535.
BRIA	21.98	6.53	0.	0.	4.	5.	25.	34.	79.	131.	115.	80.	3.	0.	476.
N'DELE	20.65	8.40	0.	0.	0.	0.	9.	15.	66.	122.	137.	44.	0.	0.	393.
OBO	26.50	5.40	0.	0.	0.	0.	17.	73.	80.	84.	83.	74.	5.	0	416.
YALINGA	23.27	6.50	0.	0.	0.	1.	20.	50.	119.	104.	138.	95.	4.	0.	531.
BRAZZAVILL	15.25	-4.26	50.	27.	38.	60.	33.	1.	0.	0.	0.	8.	107.	72.	396.
GAMBOMA	15.87	-1.88	56.	56.	62.	54.	51.	10.	0.	0.	35.	136.	121.	97.	678.
IMPFONDO	18.07	1.62	1.	0.	6.	24.	35.	54.	49.	83.	106.	98.	69.	9.	534.
MOUYONDZI	13.92	-3.98	76.	31.	58.	76.	43.	1.	0.	0.	0.	6.	129.	96.	516.
M'POUYA	16.22	-2.62	38.	46.	62.	69.	29.	0.	0.	1.	12.	61.	115.	78.	511.
OUESSO	16.05	1.62	0.	4.	1.	27.	57.	54.	37.	43.	124.	137.	78.	10.	572.
POINTE NOI	11.88	-4.81	74.	82.	109.	69.	23.	0.	0.	0.	0.	12.	106.	62.	542
SIBITI (ME	13.35	-3.68	83.	86.	97.	98.	78.	0.	0.	0.	0.	9.	197.	101.	754.
ABIDJAN AE	-5.60	5.25	0.	0.	2.	14.	150.	558.	194.	7.	9.	32.	24.	14.	1004.
ADIAKE	-3.30	5.30	0.	0.	4.	19.	128.	524.	159.	18.	27.	51.	42.	4.	976.
BONDOUKOU	-2.80	8.05	0.	0.	2.	4.	16.	35.	16.	13.	50.	40.	3.	0.	179.
DIMBOKRO	-4.70	6.65	0.	0.	5.	15.	23.	81.	49.	15.	45.	15.	1.	0.	217.
GAGNOA	-5.95	6.13	0.	2.	11.	14.	40.	122.	36.	12.	65.	56.	20.	3.	331.
MAN-AERO	-7.52	7.40	0.	0.	5.	28.	38.	73.	85.	161.	193.	58.	8.	2.	651.
ODIENNE	-7.57	9.50	0.	0.	0.	0.	6.	15.	155.	244.	174.	55.	2.	0.	651.
SASSANDRA	-6.08	4.95	0.	1.	0.	4.	78.	517.	158.	2.	0.	11.	9.	4.	784.
TABOU	-7.37	4.42	7.	0.	2.	18.	206.	447.	147.	44.	106.	64.	62.	51.	1154.
BOHICON	2.05	7.17	0.	0.	0.	9.	23.	60.	54.	31.	50.	33.	1.	0.	251.
COTONOU VI	2.43	6.35	0.	1.	3.	23.	59.	276.	131.	27.	6.	16.	6.	0.	548.
KANDI	2.93	11.13	0.	0.	0.	0.	1.	3.	41.	190.	105.	2.	0.	0.	342.
NATITINGOU	1.38	10.32	0.	0.	0.	4.	0.	10.	101.	176.	174.	33.	0.	0.	498.
PARAKOU	2.60	9.35	0.	0.	0.	1.	0.	35.	80.	108.	121.	22.	0.	0.	367.
SAVE	2.48	8.03	0.	0.	2.	4.	5.	34.	92.	70.	61.	19.	2.	0.	289.
LIBREVILLE	9.42	0.45	150.	159.	250.	223.	183.	10.	0.	0.	31.	281.	421.	221.	1930.
BITAM	11.47	2.08	1.	0.	38.	93.	103.	72.	8.	4.	101.	180.	87.	7.	693.
LAMBARENE	10.25	-0.70	62.	47.	139.	120.	81.	3.	0.	0.	12.	195.	255.	68.	980.
LASTOURVIL	12.73	-0.82	39.	45.	78.	89.	84.	7.	0.	0.	15.	151.	178.	84.	769.
MAKOKOU	12.87	0.57	12.	13.	58.	93.	83.	14.	0.	0.	24.	172.	127.	33.	628.
MAYUMBA	10.67	-3.43	164.	147.	110.	48.	32.	0.	0.	0.	0.	105.	279.	104.	989.
MITZIC	11.55	0.77	16.	15.	61.	84.	86.	12.	0.	0.	25.	182.	136.	40.	657.
MOUILA	11.05	-1.87	120.	127.	134.	136.	97.	1.	0.	0.	12.	193.	310.	147.	1277.
PORT GENTI	8.75	-0.72	136.	102.	166.	230.	105.	3.	0.	0.	0.	52.	205.	127.	1125.
TCHIBANGA	11.03	-2.85	63.	62.	94.	106.	45.	2.	0.	0.	0.	16.	149.	105.	643.
OUAGADOUGO	-1.52	12.35	0.	0.	0.	0.	0.	2.	13.	97.	43.	0.	0.	0.	156.
BOBO-DIOUL	-4.30	11.17	0.	0.	0.	0.	1.	2.	50.	159.	89.	6.	0.	0.	306.
BOROMO	-2.92	11.73	0.	0.	0.	0.	0.	2.	16.	93.	67.	1.	0.	0.	179.
DORI	-0.03	14.03	0.	0.	0.	0.	0.	1.	2.	14.	4.	0.	0.	0.	20.
FADA N GOU	-0.35	12.07	0.	0.	0.	0.	0.	0.	32.	111.	74.	0.	0.	0.	216.
OUAHIGOUYA	-2.43	13.58	0.	0.	0.	0.	0.	0.	11.	42.	10.	1.	0.	0.	64.
BOUGOUNI	-7.50	11.42	0.	0.	0.	0.	1.	4.	82.	167.	99.	16.	0.	0.	369.
GAO	-0.05	16.27	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
HOMBORI	-1.70	15.28	0.	0.	0.	0.	0.	0.	2.	3.	0.	0.	0.	0.	5.
KAYES	-11.43	14.43	0.	0.	0.	0.	0.	0.	19.	66.	32.	2.	0.	0.	119.
KENIEBA	-11.35	12.80	0.	0.	0.	0.	0.	8.	100.	276.	163.	27.	0.	0.	574.
KIDAL	1.35	18.43	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0
KITA	-9.45	13.07	0.	0.	0.	0.	0.	4.	50.	169.	93.	11.	0.	0.	327.
KOUTIALA	-5.47	12.40	0.	0.	0.	0.	2.	3.	32.	106.	68.	4.	0.	0.	215.
MENAKA	2.22	15.87	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MOPTI	-4.10	14.52	0.	0.	0.	0.	0.	0.	2.	14.	4.	0.	0.	0.	20

COMMISSION OF THE EUROPEAN COMMUNITIES - CEC

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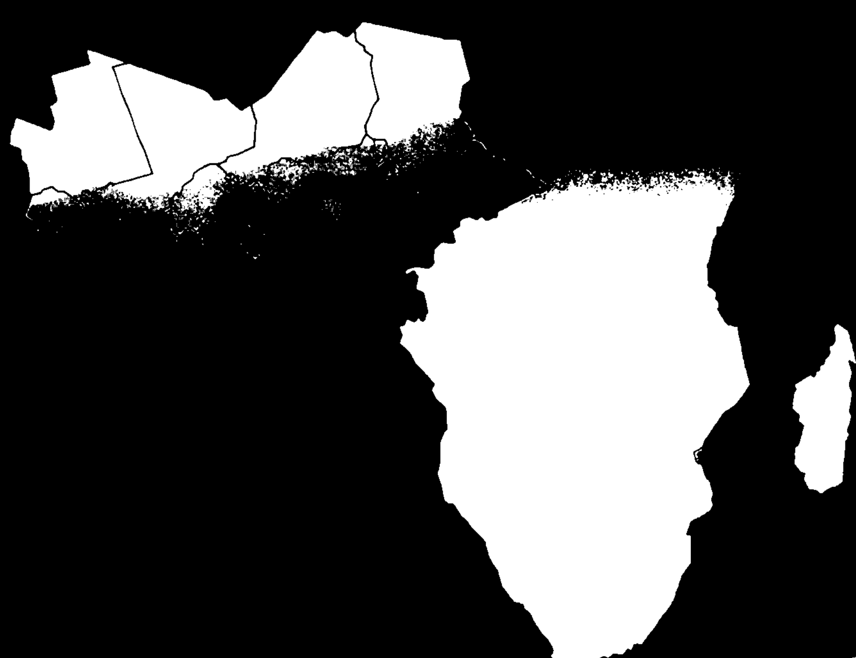
SPECIFICATIONS AND RECOMMENDATIONS FOR DATA COLLECTION

MAPPING PROGRAMME FOR ASSISTANCE IN DEVELOPMENT DECISION-MAKING



GEOHYDRAULIQUE

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S U M M A R Y

FOREWORD

The development of **mapping for assistance in decision-making,** particularly in the sector of development based on the use of groundwater, means that a number of guidelines must be respected when collecting data in the course of individual projects. This also implies that the same guidelines must be taken into consideration when planning future water programmes.

The drafting of water resource maps is dependent on the availability of homogeneous and reliable data. It should be borne in mind that the data quality required for future projects will be even greater in the context of small-scale mapping. In this case, the objective will in effect be much more precisely specified, eventually leading to the preparation of a definitive development plan. The parameters used to define data quality include the accuracy of geographical location, the representativity, and a minimum data density.

It is therefore recommended that a number of parameters be taken into account, such parameters being very carefully selected in order to ensure that there is no ambiguity as to their significance or representivity. In some cases, this will mean that satisfactory statistical processing of data populations can be undertaken.

The various parameters are subdivided into seven headings, classified depending on their importance for cartographic representation, i.e. **indispensable, minimum** (for statistical processing), or **desirable.**

The inclusion of other parameters, which can only enrich overall understanding, is not excluded. The list of parameters proprosed in these specifications represents a minimum requirement.

1 - IDENTIFICATION OF WATER POINTS

Indispensable	Minimum	Desirable
	- Type of catchwork - Condition of catchwork	- Reference n° for a given water programme - WRI (water resource inventory) number specific to a given country - Date drilled

The specifications proper to each of these parameters are as follows :

- **Type of catchwork** : borehole, observation well, water well, or other (e.g. spring).

- **Condition fo catchwork** : dry, exploited, unexploited, or other (deteriorated, disappeared, filled in).

- **Reference no.** : generally left to the initiative of those responsible for drilling programmes, although a system classification including the following components is recommended : letters indicative of a region, the number of the township, the chronological number of the water point (optional), and its number within a township,

- **Date drilled :** dated on which the water point was completed.

2 - GEOGRAPHICAL LOCATION

Indispensable	Minimum	Desirable
- Coordinates and altitude (XYZ) - Accuracy in relation to altitude Z	- Region - Department - Arrondissement - Village	- Canton - Name of district

- **Coordinates** : expressed in degrees, minutes, and seconds, or in kilometric coordinates in countries where this system exists.

- **Altitude** : ground altitude of the water point, showing the corresponding measurement accuracy and specifying whether the reading is taken from a topographic map or calculated by levelling operations.

- **Region, department, etc.** : administrative location of the water point, based on the subdivisions specific to each country.

3 - PARAMETERS USED TO DESCRIBE WATER POINTS

For purely cartographic purposes, the number of parameters to be taken into account is reduced. However, this category of parameters covers a multitude of technical factors (borehole diameter and length, drilling method, borehole type, borehole diameter, tubing length, casing length, cementation, gravel pack, etc.).

Indispensable	Minimum	Desirable
- Drilling: depth of investigation	- Depth equipped	- Drilling method - Unequipped borehole diameter

- **Depth of investigation :** actual depth of exploration hole or borehole.

- **Depth equipped :** depth of the base of the lowest section of tubing (in the case of unequipped borehole capture within the aquifer) or of the lowest section of casing.

- **Drilling method :** down-hole-hammer (DHH)
  rotary
  spudding
  mixed.

- **Diameter(s) of unequipped hole :** expressed in millimetres (mm) or in inches (")

4 - PUMPING EQUIPMENT

Indispensable	Minimum	Desirable
	- Pump installed, plus number - Depth of installation	- Type of pump - Make (optional) - Pumped discharge

- **Pumps installed** : inventory of water points equipped with a pump, of those without a pump, and of the number of pumps per water point.

- **Depth of installation** : the level of the pump casing in relation to the surface.

- **Type of pump** :
  . man-powered pump (suction and force pumps at the surface, submersible pumps)
  . motorized pumps (vertical-axis pumps, submersible electric pumps, and pumps powered by thermal, solar or eolian energy).

5 - HYDROGEOLOGY : AQUIFER STRUCTURE AND GEOMETRY

Great care must be taken when collecting data in this domain.

Indispensable	Minimum	Desirable
- Name of main water-bearing geological formation tapped	- Depth of the base of the allocthonous cover (in the case of a fissured environment)	- Name, type and rock type of secondary aquifer also tapped
- Rock type of tapped formation	- Geomorphological position (in the case of a fissured environment)	- Depth of the base of the clayey weathering zone over crystalline basement
- Type of aquifer	- Fracturing	- Use (or otherwise) of geophysics
- Depth of the base of the weathering zone or of the top of fresh basement rock (in the case of a fissured environment)		
- Depth of the top of the water-bearing formation (in the case of a porous environment)		
- Number and depth of seepage points		
- Rate of seepage flow		
- Static water level		

- **Name of main water-bearing geological formation tapped** : to be given even if the borehole is unproductive. The name is generally that of the stage (Late Continental, Hamadian, Birrimian, etc.), and the same denominations should be systematically respected for all countries and all borehole programmes. Where geological subdivisions exist, they should always be preceded by the name of the main geological formation.
- **Type of aquifer** : the type of aquifer tapped should be clearly defined (fracture porosity, matrix porosity, or mixed).
- **Lithological facies tapped** : the facies should be indicated even if the borehole is unproductive.
- **Depth of the base of the granular weathered and decayed rock** (in a fissured environment) : this reading corresponds to the interface between the basement and the weathered interval. In the case of boreholes which have not reached the

basement, the total well depth represents the minimum thickness of weathered and decayed rock.

- **Depth of the top of the water-bearing formation** (in an environment with matrix porosity) : the depth in relation to the surface and the reading in relation to the surface altitude should be recorded.
- **Number and depth of points of water inflow** : significant water influx observed during drilling. In a discontinuous environment, the depth and rate of flow of points of water influx from fractures should be recorded (each measurement corresponding to the cumulative rate of flow for all preceding points of water influx plus the new point of influx). In homogeneous terrain, evolution in the rate of flow should be recorded at regular intervals (after each string of pipes, for example). During intersection of the weathered and decayed interval, identification of the first humid zone is important (indicating the beginning of the saturated zone). Attention should be paid to auto-development phenomena.
- **Static level** : indication should be made of the initial water level below the surface measured before pumping, or of the pressure above the surface in the case of artesian wells.
- **Depth of the base of the cover** (in the case of crystalline terrain typified by a discontinuous aquifer environment) : these are allochthonous facies, generally alluvial or detrital, located above weathered and decayed rock.
- **Geomorphological position of the site of capture** (in the case of a fissured environment) : indicate whether the site of capture is :
  - . in a tabular zone
  - . in a depression
  - . in a thalweg zone
  - . in a marigot zone....
  - . in a interfluve zone
- **Fracturing** : indicate the directions of lineaments over which the water point is sited, emphasizing the most important. Where fracturing has not been taken into account, this should be specified.
- **Name, type and facies of secondary aquifer** : consideration should be made as to whether this secondary aquifer has also been tapped, or whether flow measurements have been made during drilling.
- **Depth of the base of the clayey weathered and decayed rock** (over crystalline basement) : where such weathered and decayed rock is due to weathering of the existing basement, the depth of the interface should be indicated.
- **Geophysics** : a simple indication should be given as to whether geophysics has been taken into account or otherwise, and if it has, the method used.

6 - HYDROGEOLOGY : DESCRIPTION OF PUMPING OPERATIONS, HYDRODYNAMIC AND PHYSICAL PARAMETERS

As in the case of the chapter 5, the data to be collected in this domain are essential.

Indispensable	Minimum	Desirable
- Static water level in relation to the surface - Yield, drawdown, and specific yield - Water conductivity	- Development pumping (duration and average discharge) - Test pumping (duration, discharge, drawdown) - Specific yield - Transmissivity - Storage coefficient	- Water temperature

- **Static level in relation to the surface** : depth, in relation to the surface, of the initial static level measured before pumping, or the height above the surface in the case of an artesian well.

- **Yield, drawdown, and specific yield** : indication should be made of the yield, the drawdown, and the calculated specific yield, specifying the pumping conditions under which it was obtained (development or test pumping). Care should be taken to give the most-representative measurements, preferably results obtained from test pumping. Results based on development pumping should only be given in the absence of other data.

- **Water conductivity** : expressed in microsiemens, the value for conductivity being given at a temperature of 20° Celsius.

- **Development pumping** : the total duration of development pumping and the average yield of all such pumping should be recorded for each borehole.

- **Test pumping** : the following data should be indicated for eache borehole :
  - . the number of pumping tests completed
  - . the various steps at constant discharge
  - . the duration and yield of each step, the drawdown at the end of each step, and the specific yield calculated for each step or for that regarded as the most representative.

- **Transmissivity and storage coefficient** : the transmissivity expressed in m^2/s should be shown, based on interpretation of test pumping. The same applies to the storage coefficient (nondimensional).

- **Water temperature** : expressed in degrees Celsius. The conditions of measurement should be indicated, but only measurements taken during pumping and specifically at the end of pumping tests of sufficient duration are valid.

7 - WATER QUALITY : PHYSICAL, CHEMICAL, AND BACTERIOLOGICAL ANALYSES OF WATER

The supply of clean water in a moral obligation for those who undertake the sinking of boreholes. The creation of such artificial water points confers a responsability on their creators to ensure the hygienic quality of the water distributed. This is not the case of "natural" unequipped water points, the imperfections of which have to be borne.

Any water equipment programme must therefore include determination of the hygienic quality of the water distributed to populations.

Indispensable	Minimum	Desirable
- Water temperature	- Major cations and anions	- Trace element, particularly fluorides and iodides
- Conductivity	- Nitrates, nitrites, and ammonia nitrogen	- Dissolved gases (CO_2, O_2, H_2S, where present)
- pH	- Iron and manganese - Bacteriology	

The object of sample analysis is to determine the physical, chemical, and bacteriological quality of the water in the aquifer. It is therefore essential that the sample be collected under conditions which ensure that the water sampled is representative of the aquifer as a whole. Moreover, the physical chemistry of water is characterized by a degree of temporal instability.

It is therefore important to pay particular attention to sampling conditions, to sample storage, and to the time elapsed between sample collection and analysis.

Generally speaking, programmes of sampling and measurement (in situ and in the laboratory) should not be combined with borehole programmes. The technical and temporal constraints inherent in such programmes are too severe for the guarantees required to be ensured (in relation to sampling conditions, sample storage, and the time elapsed between sample collection and analysis).

Also, programmes concerned with the hygienic quality of water should be undertaken after programmes concerned with the installation of water points. The technical staff (including the sample collector, the analyst, and the personnel responsible for data processing and interpretation) must have access to guidelines defining the rules to be respected, in such a way that the data measured will be sufficiently reliable to allow their intepretation.

GENERAL RECOMMENDATIONS

The main concern of those responsible for future water programmes will be

1. To obtain a minimum of indispensable data as featured in the list given in these specifications
2. To pay attention to the homogeneity of the data collected, by respecting the guidelines given
3. To control the reliability and representativity of the various parameters.

It is in any case recommended that an assessment of the data quality be given.

The respect of these recommendations is essential to the availability of data that can be used to build up a basic computer file which can subsequently be used for statistical processing.

Where the programme budget permits, the representative statistical parameters given priority in completion reports should be as follows.

1. The mean and standard deviation defining type-profiles, with indication of spatial variability,
2. The median, defining the most-likely values.

All these components will be used to build up the data base indispensable for the preparation of future maps. They represent a guarantee of the quality of such maps, and of their eventual use in economic development programmes.

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