ORGANISATION POUR LA MISE EN VALEUR DU FLEUVE SENEGAL (OMVS)

DEPARTEMENT DE L'INFRASTRUCTURE REGIONALE (DIR)

OMVS/USAID PROJECT 625-0958

GROUNDWATER MONITORING

ST-LOUIS / SENEGAL

HYDROGEOLOGICAL SYNTHESIS REPORT

SENEGAL RIVER DELTA

(OBSERVATION PERIOD 1986 - 1989)

VOLUME 2

WRITTEN JOINTLY BY
* OMVS/DIR/PES
* ISTI INC.
* USGS

FINAL REPORT, JUNE 30, 1990

WP.5 FILE : VL2ENG.TXT

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Through this project, OMVS aimed to acquire a hydrogeological observation system which would permit it to monitor the evolution of the upper groundwater table in relation to current and future development works in the Senegal River valley (dams and irrigated perimeters).

Analysis of the collected data should permit the study of:

a) the impact of the Diama and Manantali dams on the aquifers in contact with the river bed,

b) the rise of saline groundwater within the irrigated perimeters, especially downstream of Podor,

c) the natural recharge of alluvial aquifers and deep aquifers underlying the Senegal River valley,

d) groundwater contamination mechanisms related to the use of fertilizers and pesticides,

e) the hydrogeological potential of the different aquifers with respect to agricultural development.

1.3 Report authors

This report, available in French and English, was written by Mr. Denis Richard, consulting engineer (ISTI), in collaboration with Mr. E. Weiss, USGS expert, following systematic utilization of the GES data base (a major project output) and Groundwater software in addition to many related computer software tools (WP5, Lotus, Surfer, Grapher and others). Mr. Weiss contributed especially with the writing of chapters 6.4 (completely), 7.2.1 and 7.2.2.

Mr. Thomas Piekutowski, independent consultant under contract to USAID, wrote annexes #10 and #11. Annex #10 treats monthly average climatic parameters (4 year period: 1986-1989), and annex #11 presents monthly average hydrological data for the delta for the same period.

1.4 Project contributors

The production of this report, covering the Senegal River delta region, was made possible through the efforts of all the persons involved with the project, among whom:

* the local sector office personnel (Mr. L. Sangare, St. Louis, Senegal sector chief, Mr. A. Ndiayes, Rosso, Mauritania sector chief, and Mr. Toure, Manantali, Mali sector chief) responsible for the collection and pre-analyses of field data,

* the local central office personnel (Mr. O. Ngom, project chief, Ndar Toute, St. Louis), responsible for coordination of the field activities of each sector office.

This project, implemented by OMVS/DIR (Département des Infrastructures Régionales), benefitted from the support of technical assistance; long-term (ISTI) and short-term (USGS, BRGM et INFORMISSION).

In order to attain project goals, ISTI provided project management assistance to OMVS by assigning a consulting engineer, Mr. D. Richard, to work with the Groundwater Monitoring Unit (PES) project chief.

INFORMISSION, a subcontractor to ISTI, was responsible for the development and installation of the computer data base (GES) through the contributions of computer specialists, Mr. M. Fortin, Mr. L. Brunelle and Mr. M. Migneault.

BRGM (Mr. M. Vandenbeusch, hydrogeologist) and USGS (Mr. E. Bolke, hydrogeologist, Mr. R. Hollway, computer specialist in hydrogeological applications, and Mr. E. Weiss, hydrogeological modelling specialist), participated in orienting the data interpretation and revising objective 1).

1.5 Diverse

This synthesis report, describing the hydrogeological setting of the delta, makes extensive use of maps produced through cartographic treatment of the data. All of the maps presented in this report, and many others, can be easily consulted and printed with the GES system. In the report text, the reader will find the names of computer files (in parentheses) next to the map titles. These files, each corresponding to one map, will permit the maps to be viewed in color on the computer screen, and printed.

2 DELTA – ENVIRONMENTAL CHARACTERISTICS

2.1 Generalities

The Senegal River delta is a geographic entity of triangular form, whose apex is located at Richard Toll, a town about a hundred kilometers from the seacoast, and whose base stretches north along the coast for more than 100 km from the river's mouth. The sides of the triangle are defined by the Oualo/Dieri limits. Oualo is a local term for the river valley (floodplain) as opposed to Dieri, another local term, for the semi-desert zone on the Oualo's Northern and Southern borders. The Oualo/Dieri limits used here are those established by the S.E.D.A.G.R.I. pedological study (1973).

The Evaluation and Planning Unit of the OMVS (Cellule d'Evaluation et de Planification Continue), proposed geographical delimitations for the valley in September 1988, which were adopted by the project[1].

The Senegal River delta extends from the Atlantic seacoast to the junction of the Taouey canal and the Senegal River (PK 143).

PK signifies "point kilométrique" measured along the Senegal River. The starting point is the central pillar of Faidherbe bridge (PK 0), in St Louis.

The surface area of the delta as described by these limits is 4343 km^2. This area includes that of Lac de Guiers. The surface area of Lac de Guiers[2] changes as a function of its water level. It varies from 175 km^2 (water level = 0.0 m ASL to 275 km^2 (water level = 1.8 m ASL).

The delta region is located between latitudes 15° et 16° north.

2.2 Physical geography

2.2.1 Topography

Topographic maps at 1/50,000, indicating terrain contours (ASL), do not exist for the entire delta. The amplitude of the delta's relief is measured in meters and more generally centimeters.

The topographic characteristics of the Senegal River delta (Oualo) have been reconstituted from geostatistical calculations (Inverse Distance – 10 closest points) based on the digitized data from 12,656 elevations (ASL) within the Oualo – floodplain.

The sources of topographic information used for this compilation were numerous and of various types: topographic maps at 1:50,000 partially incomplete, photogrammetric compilations (EIRA mosaics at 1:50,000) produced from aerial photographs, and topographic measurements, of some areas, taken during construction of irrigated perimeters in the delta.

The reader may refer to map #1 "Oualo topography (m ASL) (dlt_top)" which follows. This map also indicates the location of the OMVS piezometric observation network points (wells = half-blackened squares, piezometers = blackened circles).

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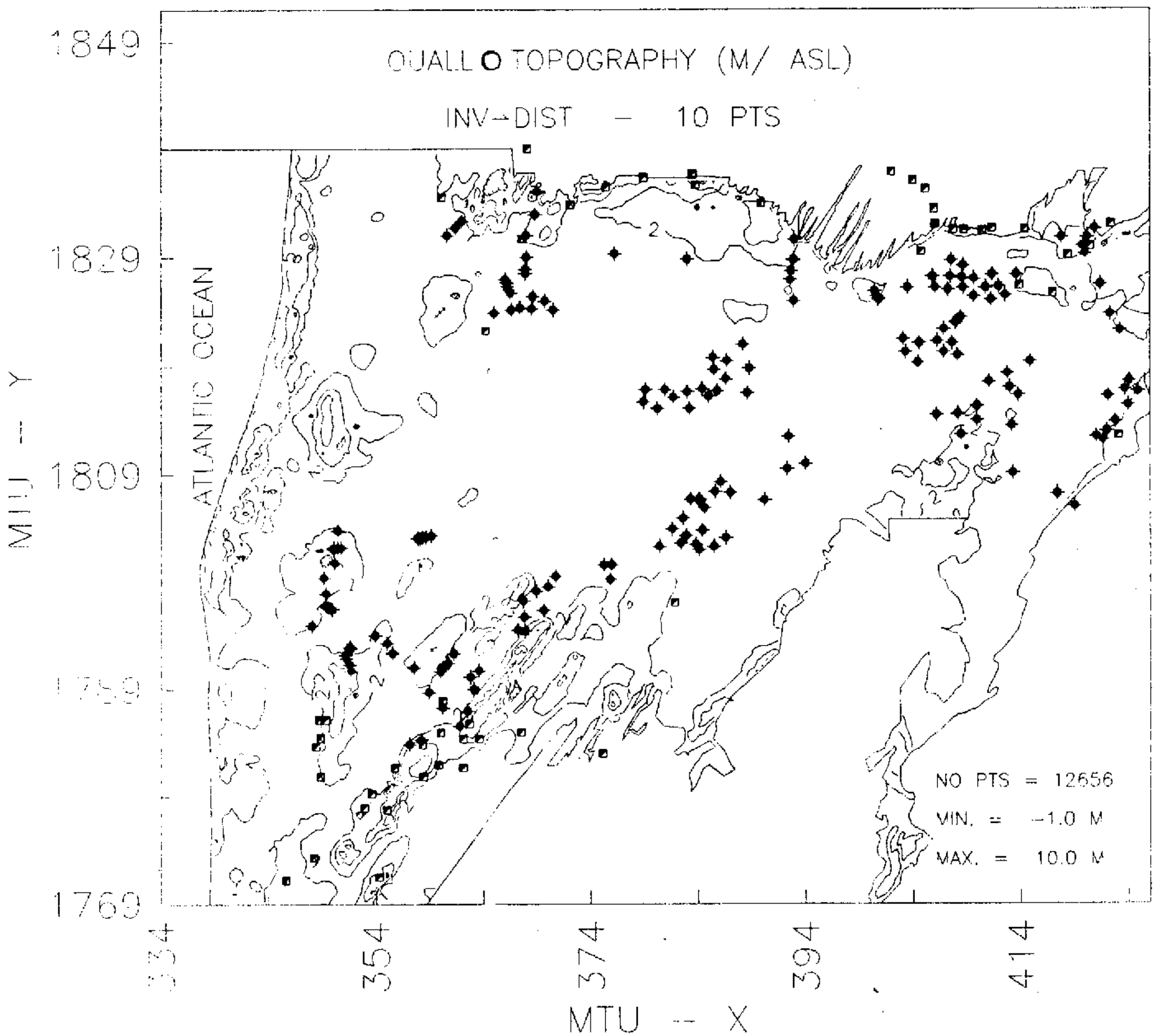
[1] Ref.: OMVS\CEPC, Sept. 1988, p.3.

[2] Ref.: COGELS et al., 1982, p 46.

SENEGAL RIVER – DELTA REGION

SCALE : ———— = 10 Km

MAP Nº 1



Contour line spacing is 3 meters and the first visible contour is the one at two (2) meters. Minimum and maximum values are from -1 to 10 meters. The distribution of hypsometric plane surface areas by GN (ASL) elevation classes, for the entire delta (Mauritanian and Senegalese) is:

ELEV. ASL	AREA KM^2	% TOTAL AREA
<10	4343.8	100.00%
<8	4325.6	99.58%
<5	4172.5	96.06%
<3	3754.5	86.43%
<2	3206.9	73.83%
<1	1668.0	38.40%
<.5	426.9	9.83%
<0	26.5	0.61%

The surface area of the Mauritanian delta is 1664 km^2 and that of the Senegalese delta is 2679 km^2.

The relief is extremely flat, generally below 2.0 meters in elevation (73.83% of the surface area of the delta is below 2 meters), especially in the central part of the delta. The most notable elevations are associated:

* with the toundous - a local term for the ancient dunes originating from Ogolian sediments. These topographic forms are identified by the 2 meter contour lines. These dunes are aligned in a North-South direction on each side of Diama dam and Mbell dike and in a N.E.-S.O. direction between the Lampsar swamp and the Oualo/Dieri boundary,

* with the recent coastal dunes which can sometimes attain 15 meters in elevation.

In the Dieri, ASL elevations vary between 5 and 15 meters. In any case the relief is insufficiently known and, consequently, non-digitized.

It should be recognized that this topographic map has been prepared to meet the project's hydrogeological needs, not those of delta developers.

2.2.2 Hydrographic network

The bed of the Senegal River is wide in the delta region (up to 800 m), even during the dry season, and quite deep (16 meters in places, see annex 1). The network of watercourses is spatially fixed (no lateral displacement observed) and the water surface, from Richard Toll to the river's mouth has a slope of 0,6 cm/km[3].

The Senegal River has many connected watercourses in the delta:

* on the right bank, the Ndiadier, the Mbell, the Gouere, the Garak,

* on the left bank, the Djoudj, the Gorom, the Djeuss, the Lampsar.

Before the development of a surface water management system, all of these sloughs were branches of the river, i.e., they filled with the river's floodwater and slowly emptied as the level of the connected, unrestrained water bodies dropped following the rainy season. Uncontrolled, they dried up.

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[3] Ref.: P.N.U.D./F.A.O., 1977, p. 30.

Today, because of surface water control structures, most of these watercourses are, for at least part of their length, permanent. These sloughs are used as natural irrigation and drainage canals. They are artificially maintained at suitable levels during the three "theoretically possible" rice production cycles: rainy season (hivernage - HIV) from July to October, cool dry season (contre saison froide - CSF) beginning sometime in October, and the hot dry season (contre saison chaude - CSC) beginning sometime between mid February and mid March.

2.3 Agricultural development - current and planned

Because of annual deposits of silt by the floodwater, the Senegal River delta is a zone of high agricultural potential, as shown by the current and planned agricultural developments. It is, by far, the most developed of the agricultural regions of the valley.

Agricultural development has accelerated since completion of the dams at Diama (Senegal River delta) and Manantali (Upper Basin). These dams entered service in November 1986 (Diama) and July 1987 (Manantali). The joint operation of these dams increases the agricultural potential of Ouallo land by regularizing the natural flood (Manantali dam) and by impeding the annual influx of saline water[4] (Diama dam).

The usable agricultural land area (superficie agricole utile - SAU)[5] of the delta is between 33,800 ha and 134,384 ha. The lower limit was determined by a topographic and geomorphological analysis of the delta (CHAUMENY, 1972)[6] and the upper limit by a pedological analysis of the delta's agricultural soils (S.E.D.A.G.R.I. 1973)[7].

(SAU) is the cultivable land area. It is calculated by subtracting non cultivable land areas from the total land area (surface brute - SB):

* protected forests and reserves,
* water bodies (permanent swamps and watercourses),
* towns, villages, roadways, communication and power lines,
* non cultivable areas because of poor soil or land quality (pedological or geological), lack of drainage, relief, salinity, etc,.

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[4] See GAC et al., 1986.

[5] Ref.: PES, 1989.

[6] Ref.: P.N.U.D.\F.A.O., 1977, table 6, P. 253, Delta: non saline and easily desalinated.

[7] Ref.: P.N.U.D.\F.A.O., 1977, table 4, p. 250 and p. 21. SAU = total land area for land use classes 1, 1R, 2, and 2R (classes 6 and 6R excluded). Planimetry performed by the St. Louis sector chief. The land use classes are defined as follows:

CLASS 1 : EASILY IRRIGABLE
CLASS 2 : IRRIGABLE
CLASS 1R : SUITABLE FOR RICE
CLASS 2R : SUITABLE FOR RICE
CLASS 6 : NON IRRIGABLE (saline soil)
CLASS 6R : NON IRRIGABLE (coarse texture, no drainage, irregular topography).

For the reference year 1987, the net developed, irrigable land area of the delta (superficies aménagées nettes irrigables - SNI) totaled 20059 ha and the cultivated area (superficies cultivées - SC) totaled 10270 ha. In relation to the cultivated land area (SC), the agricultural potential of the delta was exploited to only 30.4% or 7.6%, according to the limit used.

(SNI) is the land area which could effectively be irrigated and cultivated. It is calculated by subtracting from the total agriculturally developed land area (superficie agricole utile - SAU), the land areas occupied by construction and development works: dikes, irrigation and drainage canals, roadways, threshing areas, buildings, etc..

(SC) is the part of the SNI actually cropped during a given agricultural season. It is always less than or equal to the SNI and corresponds to developed areas effectively under cultivation for the season concerned.

With respect to the delta's total geographic surface area (4343 km^2), the cropped area (SC) under irrigated rice cultivation (102.7 km^2 in 1987) represented 2.36%.

If we retain the upper limit for the cultivable land area (SAU) of the delta (1343.84 km^2 - S.E.D.A.G.R.I.) and we suppose that all of this potential area be irrigated, then we can conclude that 30.9% of the geographic surface area of the delta would be under irrigation.

3 DELTA - HYDRAULIC INFRASTRUCTURE

3.1 Dikes

As part of its agricultural development, the delta's hydraulic network has greatly evolved since 1964, when the peripheral dike along the left bank of the Senegal River was completed. This dike allowed the planners and managers of agricultural development (left bank of the delta) to begin large scale irrigated agriculture with a planned system of water supply and drainage.

The equivalent dike on the right bank of the delta does not yet exist (March 1990), although work on it is under way.

The emplacements of these dikes (LB = existing and RB = under construction) and the limits of the large irrigated perimeters are shown on map #2 "Locations of large perimeters and dikes - right and left banks (dlt_str)" (lines parallel to the river = dikes; shaded areas = large irrigated perimeters).

Since 1964, the left bank of the delta has been exempted from the annual cycle of flooding corresponding to the passage of the flood and the rainy season. The dike has permitted agriculture in the delta to develop from a stage of controlled submersion to one of large scale irrigated agriculture with complete control of the water resource.

In the absence of a dike on the right bank, the floodwater spill over annually there. The distribution of hypsometric plane surface areas by ASL elevation classes, for the right bank of the delta, and the storage capacity in millions of cubic meters by class is:

ELEV ASL	AREA KM^2	VOLUME 10^6 m^3
<10	1664.0	NA
<3	1348.5	NA
<2.5	1220.3	1,287
<2	995.7	776
<1.5	676.2	385
<1.25	534.5	257
<1	385.0	152
<.5	135.0	42

Examination of Figure #1 shows that monthly average river levels have risen to and stayed at 1.25 meters, for periods of 3 to 6 months, depending on the year concerned. This level corresponds to a maximum storage volume of 257 millions cubic meters, if the time was sufficiently long to permit filling of the various sloughs to their storage capacities, and if the sloughs were hydraulically linked.

3.2 Hydraulic control structures

Water management works (dams, roads, gated water control structures, etc.) located within the delta limits on the right and left banks are listed in table #1. Many of these structures are located in the left bank dike at the mouths of watercourses and sloughs while others are installed along the watercourses.

SENEGAL RIVER – DELTA REGION

SCALE : = 10 Km

MAP Nº 2

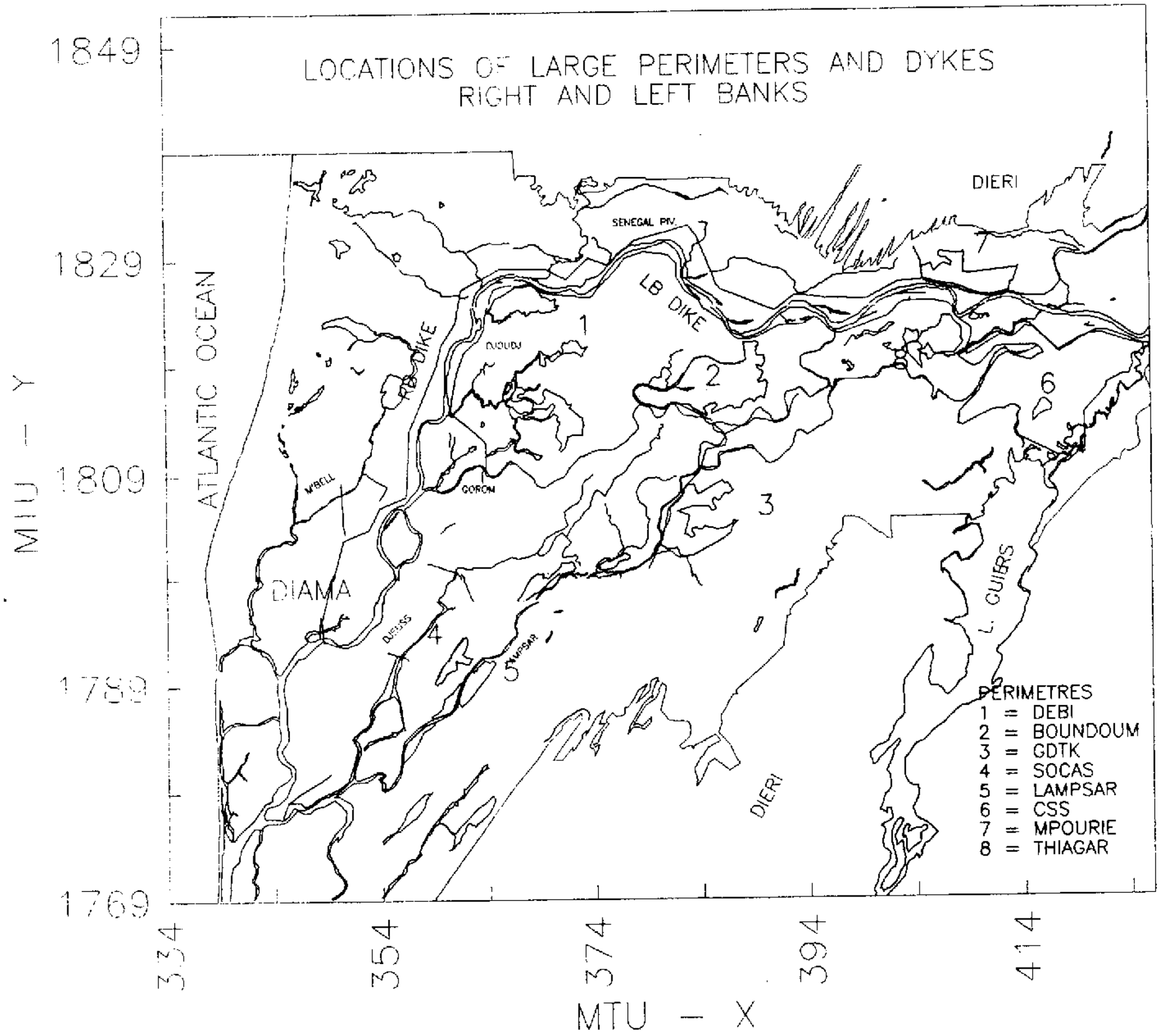

Table #1 - Delta - Left Bank (LB) and Right Bank (RB) - List of dams and gated structures already existing during the period 1986-1989.

BANK	STRUCTURE NAME	MTU-X	MTU-Y	WATERCOURSE	MANAGED Y/N
LB	PONT BARRAGE DE BANGO	344.2	1777.9	LAMPSAR	Y
LB	BARRAGE DE DIAOUDOUM	350.6	1776.7	N'GALAM	Y
LB	OUVRAGE J KEUR MOMAR SOW	356.4	1792.2	DJEUSS	N
LB	BARRAGE DE MAKHANA	354.5	1781.3	LAMPSAR	N
LB	PONT BARRAGE DE NDIOL	361.3	1787.0	LAMPSAR	Y
LB	PONT BARRAGE DE ROSS BETHIO	377.8	1800.2	LAMPSAR	Y
LB	OUVRAGE DE N'DONG	385.7	1813.7	LAMPSAR/GOROM AM	N
LB	OUVRAGE DE DIAMBAR	396.2	1816.6	GOROM AM	N
LB	OUVRAGE DE DIOVOL	396.2	1817.4	GOROM AM	N
LB	OUVRAGE G GOROM	364.7	1810.0	GOROM AV	N
LB	OUVRAGE W DE GAELA	382.4	1815.8	GOROM AV	N
L+R	BARRAGE DE DIAMA	349.0	1794.1	FL. SENEGAL	Y
RB	DIGUETTE M'BELL	350.9	1808.0	M'BELL	N
LB	OUVRAGE I	356.5	1797.4		N
LB	OUVRAGE H DE THIENG	360.5	1804.3		N
LB	OUVRAGE F DU DJOUDJ	361.9	1815.2	DJOUDJ	Y
LB	OUVRAGE E DE DEBI	364.9	1823.0		Y
LB	OUVRAGE D - ILE AUX CAIMANS	376.0	1826.9	DJOUDJ	Y
LB	OUVRAGE C DE THIAOUWAR	389.1	1821.5		N
LB	OUVRAGE B DE RONCQ	397.0	1821.6	GOROM AM.+LAMPSAR	N
LB	OUVRAGE A DE THIAGAR	408.8	1822.5		N
LB	OUVRAGE DU NDIADIER	364.7	1827.2	NDIADIER	N
LB	PONT ROUTE TAHOUEY	425.8	1820.7	TAHOUEY	Y

SOURCE: SAED - Hydraulic Map (year unknown)

The locations of these hydraulic structures as well as those of raingauges, water level scales, and some towns are indicated on map #3 "Locations of Hydraulic Structures, Raingauges, Water Level Scales (dlt_equi)", (black square = dam or gated structure; dagger = water level scale; triangle = raingauge; circle = town).

The structures listed which were used during the period 1986-1989 are indicated by the letter Y in the column "Managed Y/N"[8]. All these structures were equipped (still are) with water level scales set to zero ASL, but few were observed except for the scales located up and downstream of Diama dam, the bridge-dam at Dakar Bango and the road-bridge over the Tahouey.

Brief descriptions of the operation of the structures which were used during the period follow.

DIAMA DAM

Diama Dam, completed in 1986, began functioning in November, 1986. Figure #1 indicates the annual water level variations upstream of the dam. During the period of piezometric observation by the project (1986-1989), the monthly average level upstream of Diama Dam varied from -0.26 to 1.37 m (see figure #1).

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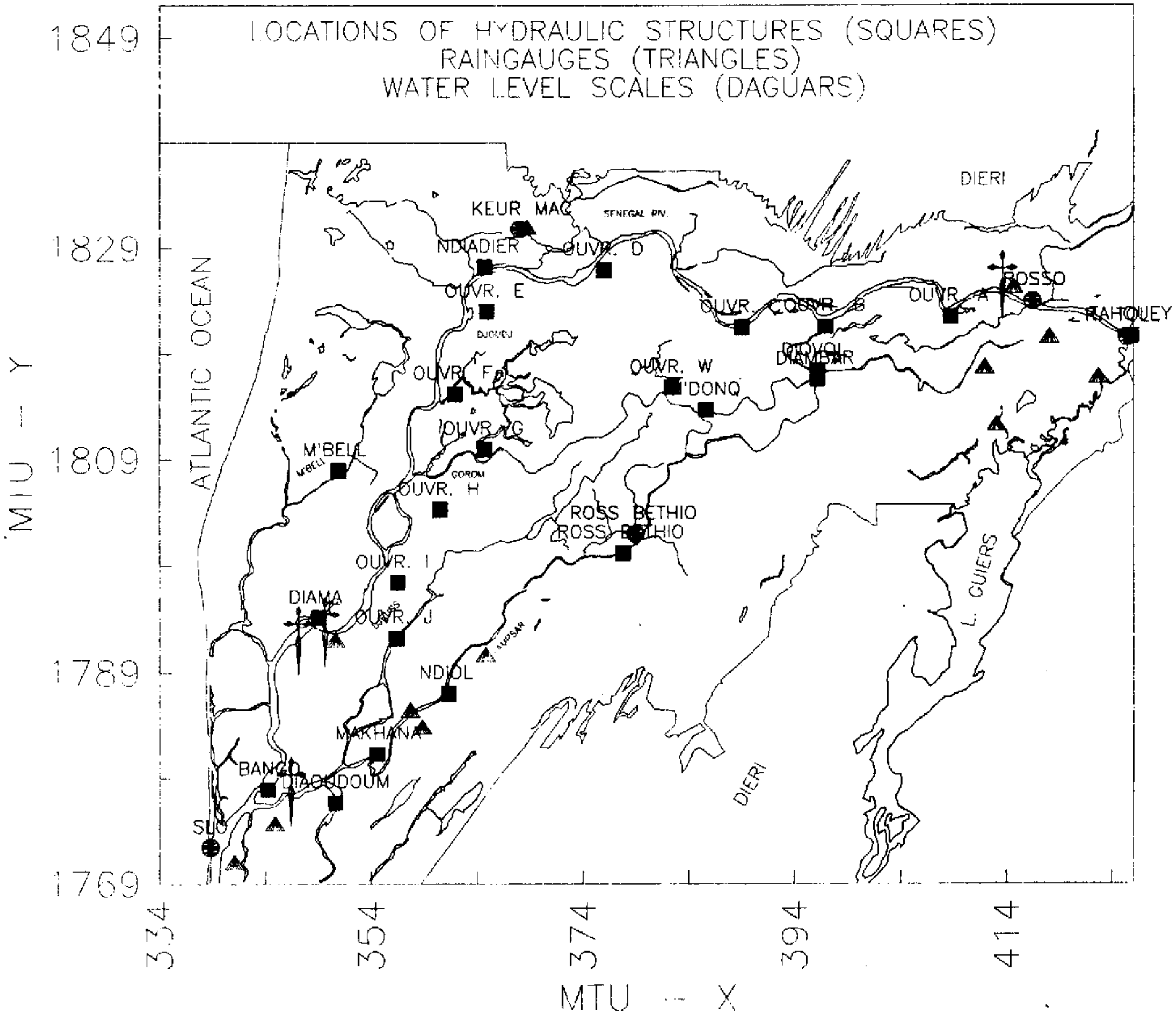
[8] Personal communication with Mr. J. Petolon, technical adviser to SAED.

SENEGAL RIVER - DELTA REGION

SCALE : ⎵⎵⎵ = 10 Km

MAP Nº 3



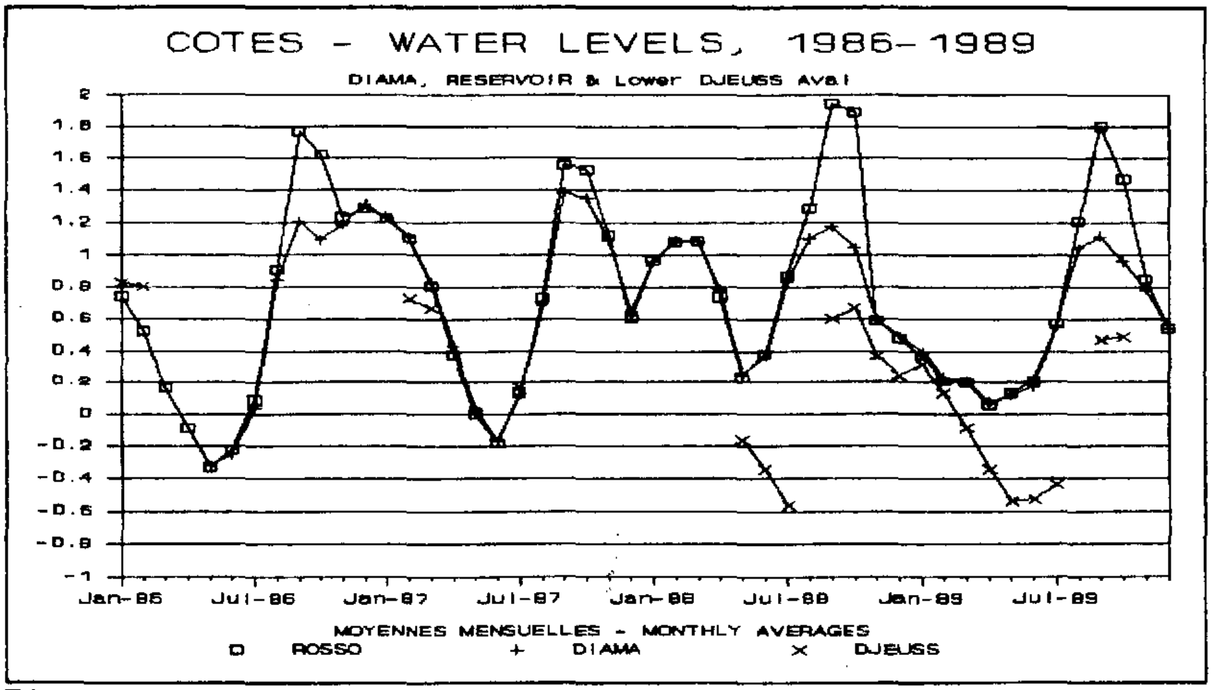


Figure 1 Delta - annual water level fluctuations

Since that time the salt wedge, which had previously ascended the river during the dry season, has been halted. This is partly true inasmuchas the joint operation of the Diama and Manantali dams became possible in July, 1987, one year after Diama Dam entered service. The completion of the dams at different times forced Diama Dam managers to partially open the gates at the end of the '86-'87 dry season, allowing an entry of salt water.

The level expected to be maintained upstream of Diama Dam, upon completion of the right bank, will vary between 1.5 m and 2.5 m. These levels will create reservoirs that extend, respectively, East of Boghe (PK 395) or East of Cas-Cas (PK 442)[9].

It can be seen that water level variations at Rosso are the same as those at Diama, except during the flood (1988). These water level variations are closely related to the management of Diama Dam during the period July 1986-July 1987, and to the joint management of Manantali and Diama Dams after July 1987.

The fluctuations of the water level are artificial and partially controlled by the managers of the OMVS common works (Diama and Manantali) in response to agricultural needs and the requirements posed by construction of the dike on the right bank.

---

9 Ref.: GERSAR 1983.

ROAD-BRIDGE OVER THE TAHOUEY

The Tahouey canal, linking the river and Lac de Guiers (Lake) - a fresh water reservoir for Dakar - and the Senegal River, is controlled by a gated structure, which is also a road bridge in Richard Toll.

This is a gravity-fed structure. During passage of the floodwater, at the end of the rainy season, the gates are opened to allow filling of Lac de Guiers[10]. Besides this seasonal influx, the Lac de Guiers is very slightly recharged by rainfall and runoff but not at all by the groundwater since its level is always greater than the surrounding potentiometric surface. From now on, with Diama Dam and the discharges from Manantali Dam, it will be possible to fill Lac de Guiers by means of Tahouey canal even during the period after the flood.

VANNE MBELL DIKE

This structure was built as a temporary means, in the absence of a dike on the right bank (under construction in late 1989), to keep water from flowing around Diama dam by way of Mbell slough during the dam's construction. Upon completion of the right bank dike, this structure will become useless since it is situated outside the reservoir as defined by the right and left peripheral dikes.

GATES D and E to DJOUDJ - NATIONAL PARK

This structure is located in the left bank and controls the water level in the Djoudj swamp, essential for preservation of the park's bird population.

NDIADIER GATED STRUCTURE

This structure was built during construction of Diama Dam and will be integrated into the right bank dike. It will permit filling from Diama reservoir of the large Aftout-Es-Sahel depression (negative contours) which parallels the Mauritanian coast north of the delta. Development of this depression (agriculture, aquifer recharge) has not yet begun. It will require construction of N'Diadier canal.

BOUNDOUM DAM (Ouvrage de N'Donq)

This old structure separates the upstream and downstream portions of the Gorom slough and directs the water pumped at the Roncq station into Lampsar slough, whose middle portion is used as a natural irrigation canal for several irrigated perimeters (Grande Digue Tellel Kassak and Lampsar) and whose downstream section is a natural fresh water reservoir for the city of St. Louis.

Water levels in the middle sections of Lampsar slough are controlled by the Ndiol and Ross Bethio bridge-dams. Water levels in the downstream sections of the Lampsar are controlled by the Dakar Bango and Ndiol bridge-dams.

---

[10] Ref.: ISE - 1983.

3.3 Current irrigation systems

In the left bank of the delta, SAED[11] manages the utilization of many irrigated perimeters (Débi, Boundoum, Grande Digue-Tellel-Kassak Nord and Sud, Thiagar, Balky, Sousse, Dombo). SOCAS[12] operates the perimeter at Savoigne, ISRA[13], has an experimental perimeter at N'Diol, and CSS[14], operates the sugar plantation at Richard Toll. This plantation extends beyond the limits of the delta.

In the left bank of the delta, SONADER[15] manages the Chinese perimeter at M'Pourié, near Rosso.

A large number of small, village-operated irrigated perimeters (périmètres irrigués villageois - PIV) are associated with the large perimeters on both banks of the river. Many have been established recently, following inauguration of Diama Dam in November, 1986, and most benefit from the water supply systems managed by the large operators: SAED (Sénégal), SONADER (RIM) and agribusinesses (Sénégal).

Table #2 lists the large perimeters which constitute the principal water supply systems, identifies their main pumping station and the destination of their drainage water.

Table #2: DELTA - LARGE IRRIGATED PERIMETERS (SAED, SONADER, PRIVATE)

OPER. ORGAN.	MAIN PUMPING STATION	WATER SOURCE	PERIMETERS SERVED	NOMINAL LAND AREA HECTARES	DRAINAGE WATER DESTINATION
SAED	RONCQ	RIVER	13 CUVETTES LAMPSAR	2500	NOAR + KANKRAYE
SAED	RONCQ	RIVER	SOCAS, ISRA		PARDIAGNE
SAED	RONCQ	RIVER	GRANDE DIGUE TELLEL	2175	N'DIAEL
SAED	RONCQ	RIVER	KASSAK SUD	527	N'DIAEL
SAED	RONCQ	RIVER	KASSAK NORD	800	N'DIAEL
SAED	THIAGAR	RIVER	THIAGAR	1900	DIOVOL
SAED	THIAOUWAR	RIVER	BOUNDOUM	3200	LOWER GOROM
SAED	DEBI	RIVER	DEBI	1500	RIVER
SAED	GROUPE MOTO POMPE	TAHOUEY	NDOMBO	300	OLD TAHOUEY
SAED	GROUPE MOTO POMPE	TAHOUEY	THIAGO	500	OLD TAHOUEY
PRIVATE	CSS	RIVER	CSS, BALKY, SOUSSE	7500	DIOVOL/LAC GUIERS
SONADER	MPOURIE	RIVER	MPOURIE	1216	RIVER

The water is currently supplied to the large perimeters[16] in several different ways:

---

[11] SAED: Société d'Aménagement et d'Exploitation des terres du Delta, de la vallée du Sénégal et de la Falémé.

[12] SOCAS: Société de Commercialisation Agricole du Sénégal.

[13] ISRA: Institut Sénégalais de Recherche Agricole.

[14] CSS: Compagnie Sucrière du Sénégal.

[15] SONADER: Société Nationale d'Equipement Rural.

[16] Ref.: GERSAR CACG, EUROCONSULT, SIR ALEXANDER GIBB & PARTNERS, SONED-AFRIQUE, Plan Directeur de la rive gauche, draft, June 1989, p. 6 and 57.

* perimeters along the Tahouey canal and Lac de Guiers; direct pumping from these sources,

* perimeters along the river; gravity flow through water control structures during the rainy season, and by direct pumping from the river during the dry season,

* Djoudj Park; gravity flow during the rainy season,

* along the Gorom/Lampsar slough; by pumping from this channel which is itself filled by gravity flow during the rainy season and by pumping during the dry season (Roncq pumping station).

The current drainage systems into the depressions and swamps function by gravity and pumping.

All the perimeters - large and small (PIV) - are inventoried yearly by the OMVS Evaluation and Planning Unit (CEPC). This inventory permits the annual and seasonal determination of the cultivated land area (SC). The situation for the reference year 1987 is given in section 2.3.

3.4 Sections and sub-sections of the delta watercourses

Management of the surface waters by means of control structures (see section 3.2) cuts the delta watercourse network into the sections and sub-sections described in table #3.

Each of the sections has its own hydraulic conditions. Characteristic dry and rainy season conditions, in the zones for which water level data has been recorded, are described in annex 2 for the period 1987 to 1989. The periods chosen for each of the seasons on the hydrogeological maps are:

* dry season (end of the dry season): from May 15 to July 15
* rainy season: from August 15 to October 15

Characteristic rainy season conditions in the zones for which no water level data exists (lower Gorom and the Lampsar), will be deduced:

* the Lampsar; from a theoretical[17] graph and from field measurements for the dry season, (March 1988)[18].

* the lower Gorom; from field measurements[19] made between 10/15/80 and 2/20/81.

This sectioning allows the hydrogeologist to analyze shallow water table piezometric variations in relation to surface water conditions. The surface waters are affected by management of the delta water supply infrastructure and vary with the agricultural seasons and climatic conditions.

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17 Ref.: GERSAR, EUROCONSULT, SIR ALEXANDER GIBB, SONED-AFRIQUE, June 1989, figure 2.6, p. 43.

18 Ref.: same document, p. 6.

19 Ref.: SAED, 1980.

Table #3: Delta watercourse network - Sections and sub-sections

#	ZONES	REMARKS	MEASUREMENT APPARATUS
1	ATLANTIC	SEACOAST	= 0 M ASL
2	LAC DE GUIERS	VARIABLE WATER LEVEL DURING THE YEAR FILLED THROUGH TAHOUEY CANAL FRESH WATER RESERVOIR FOR THE CITY OF DAKAR	WATER LEVEL SCALES SANENTE, GNITH, RICHARD TOLL
3	LOWER DJEUSS LOWER LAMPSAR	VARIABLE WATER LEVEL DURING THE YEAR FILLED BY RONCQ STATION AND OPENING OF THE DAKAR BONGO BRIDGE-DAM ZONE DEFINED BY KEUR MOMAR SOW CONTROL STRUCTURE, BONGO BRIDGE-DAM, NDIOL BRIDGE-DAM	WATER LEVEL SCALE DAKAR BANGO
4	MIDDLE LAMPSAR	VARIABLE WATER LEVEL DURING THE YEAR FILLED BY RONCQ STATION AND OPENING OF THE ROSS BETHIO BRIDGE-DAM ZONE DEFINED BY NDIOL BRIDGE-DAM, NDONQ CONTROL STRUCTURE	NONE, DEDUCTION FROM "SCHEMA DIRECTEUR DU DELTA ANNEX C, SCHEMA HYDRAULIQUE JUNE 89"
5	LOWER GOROM	VARIABLE WATER LEVEL DURING THE YEAR FILLED THROUGH GAELA STRUCTURE, AFTER BOUNDOUM PERIMETER DRAINAGE ZONE DEFINED BY G STRUCTURE (LEFT BANK DIKE) AND NDONQ STRUCTURE	NONE, DEDUCTION FROM INTERNAL SAED DOCUMENT "QUELQUES OBSERVATIONS SUR LA FLUCTUATION DU NIVEAU D'EAU DANS LE GOROM AVAL CAMPAGNE 1980/1981"
6	DJOUDJ	VARIABLE WATER LEVEL DURING THE YEAR GRAVITY FILLED THROUGH D AND E CONTROL STRUCTURES ZONE DEFINED BY THE DJOUDJ AND ITS TRIBUTARIES	NATIONAL PARK
7	DIAMA RESERVOIR ROSSO UPPER MBELL	VARIABLE WATER LEVEL BY HYDRAULIC MANAGEMENT OF DIAMA AND MANANTALI DAMS ZONE DEFINED BY DIAMA DAM, PK 143, MBELL CONTROL STRUCTURE	WATER LEVEL SCALES DIAMA RESERVOIR + ROSSO
8	DIAMA DOWNSTREAM UPPER MBELL	VARIABLE WATER LEVEL INFLUENCED BY TIDE ZONE DEFINED BY DIAMA DAM, MBELL CONTROL STRUCTURE (DOWNSTREAM PART)	WATER LEVEL SCALE DIAMA DOWNSTREAM

3.5 OMVS piezometric network

Within the delta limits, the Groundwater Monitoring Project was responsible for the construction of a piezometric network of 252 piezometers. The delta part of the entire OMVS network totals 306 observation points of which 54 are village wells and 252 are piezometers. The map #4 "OMVS piezometric network, locations of wells and piezometers (dlt_a_b)" indicates the distribution of wells and piezometers (black circle = piezometer; half-blackened square = village well).

The ▬ lines on this map, coded "L (number)", indicate lines of piezometers transverse to the Senegal River and/or within the limits of large irrigated perimeters, and for which piezometric profiles have been traced (see annexes 8 and 9).

The OMVS piezometric network, irregularly distributed in the delta, permits hydrogeological observations to be made at local and regional scales. It contains:

* 26 village wells on the left bank and 28 on the right bank,

* 173 piezometers on the left bank and 79 on the right bank.

The wells are generally located at the Oualo/Dieri limits. More[20] than one fourth of the works (wells + piezometers) are within 500 meters[20] of permanent watercourses (see section 2.2.2 of this report), likely to influence the groundwater resource.

The piezometric network pla[21]cement criteria were defined in the Terms of Reference of the project document[21].

In general terms, these criteria are:

1) one piezometer/100 ha within the confines of the large irrigated perimeters (short piezometers).

2) 10 pre-selected piezometric profiles (kilometric scale) transverse to the Senegal River valley (short, medium and deep piezometers).

3) approximate density of one piezometer/100 km^2 (short, medium and deep piezometers).

4) some piezometric profiles (metric scale) transverse to the river in the zone influenced by Diama Dam (short and medium piezometers).

5) one piezometer per distinct geological formation, according to the probable shape of deep under-lying aquifers.

Point #5 allowed for the construction of two and sometimes three piezometers at the same geographic site, each installed in a different geological target.

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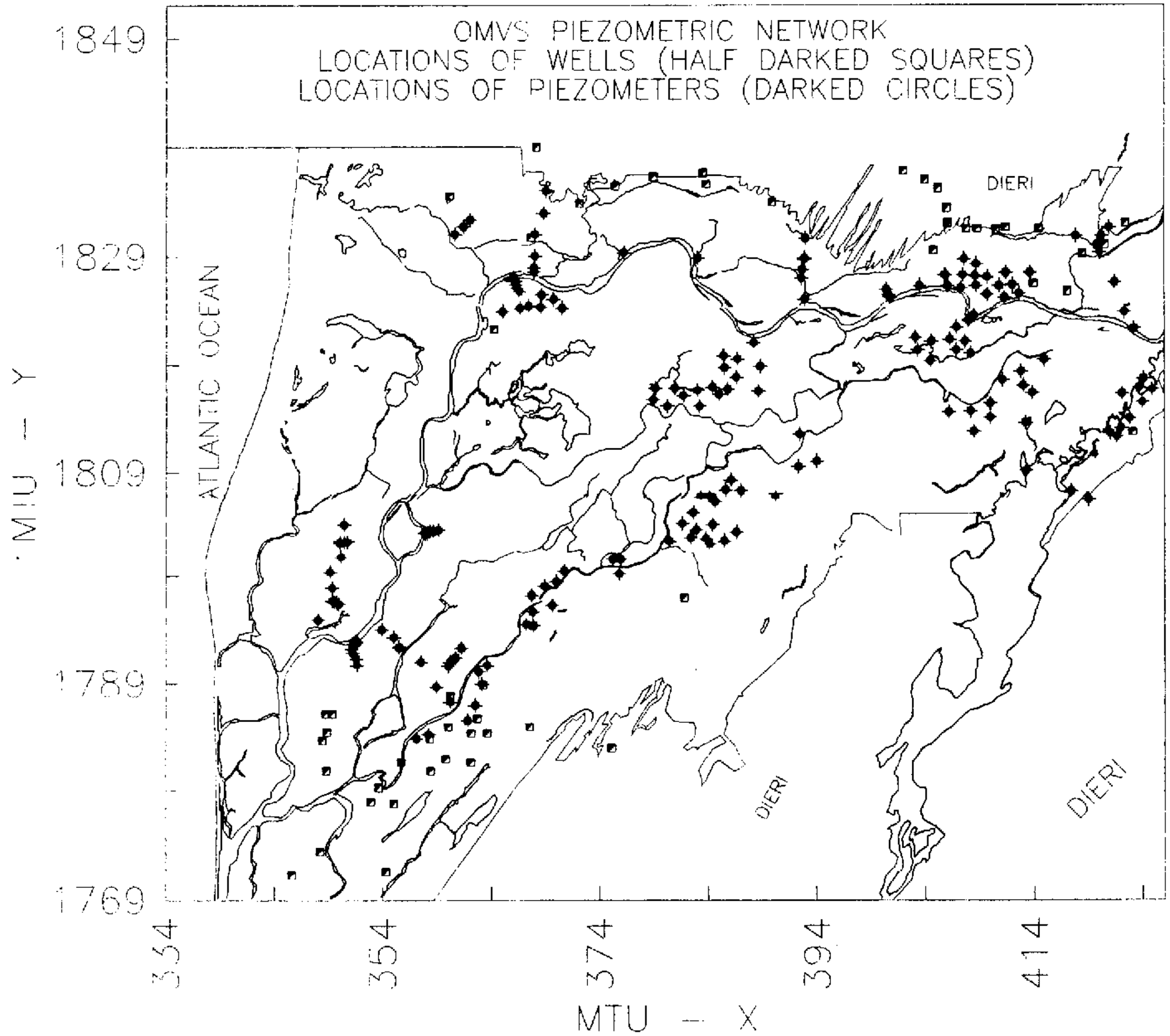
[20] See annex #3, figure #3.

[21] AID, 1983.

SENEGAL RIVER – DELTA REGION

SCALE : ⊢——⊣ = 10 Km

MAP Nº 4



4 DELTA - AQUIFER CHARACTERISTICS

4.1 A priori description

Within the confines of the delta, the project performed 6 pumping tests in unconsolidated, sedimentary terrain (see the locations map #12 following page 28).

The pumping test sites have very similar aquifer formations. They are schematically described as follows:

0 -------------	
LAYER #1	surface layers are a combination of horizontal strata composed of silt and clay, sometimes fine sand, belonging to Recent/Sub-recent sediments[22]. Together, these strata form the semi-permeable layer #1.
4/5 m ----------	
AQUIFER I	relatively homogenous aquifer, made of fine sands. These sediments are usually Nouakchottian deposits, and, sometimes, upper Inchirian sediments.
15/18 m -------	
LAYER #2	a combination of horizontal strata composed of silt and clay. Total thickness varying from a few to many meters. These stratified layers are upper Inchirian sediments, and, sometimes, lower Nouakchottian sediments. Together, these strata form the semi-impermeable layer #2.
19/30 m -------	
AQUIFER II	heterogenous aquifer composed of fine to medium grained sands with a significant silt content. These sediments are located in the Inchirian sediments.
40/50 m -------	

The geographic distribution of the pumping test sites within the confines of the delta and the geometric similarity of the aquifer formations examined (on a local scale) infer that similar aquifer formations underlie the entire delta (regional scale).

The structural description presented above, without the description of the geologic formations, was also noted in the Audibert[23] report conclusions.

The sediments of semi-permeable layer #1 (clay and/or silt) were described in detail in the P.N.U.D/F.A.O. (1977) pedological and geomorphological study. Local terms for the various soil types (textural distinctions) based principally on clay content[24], are: Hollalde, Faux Hollalde and Fonde.

HOLLALDE	55 % < % CLAY
FAUX HOLLALDE	30 % < % CLAY < 55%
FONDE	% CLAY < 30%

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[22] The reader will find, in annex 3, detailed geological descriptions, and accompanying maps, of the stratigraphic series encountered in the delta.

[23] Ref.: Audibert, 1970, document II, p. 31.

[24] P.N.U.D./F.A.O., 1977, p. 265, table 19.

Lateral extensions of aquifer I, including the semi-permeable layer #1, are limited:

* to the North and South by the Oual1o/Dieri limits (see section 2.1 of this report), which define the delta floodplain,

* to the West, by the seacoast,

* to the East, by the delta limits. These formations continue Eastward beyond the delta limits,

Lateral extensions of aquifer II, including the interlaminate, semi-permeable layer II are limited:

* to the East, by the geological boundary proposed by Audibert[25] and structurally confirmed by the DHE[26].

* to the North and the South, by the limits of the maps produced here. These formations extend beyond the map borders.

4.2 Geostatistical description

The vertical and horizontal geological heterogeneity indicated in all the data collected by the Groundwater Project, as well as that included in the Audibert report, makes the task of describing the geometry of the aquifer very difficult on a regional scale (delta). In the effort to make such a description, the project used a geostatistical approach (Kriging) based on the theory of regional variables. The calculations were made with the help of SURFER[27] computer software.

The following premises were associated with the geostatistical approach:

1) semi-permeable layers #1 and #2 are defined, first of all, *granulometricaly*, as contiguous, juxtaposed stratigraphic horizons composed of silts and/or clays. In other words, if two or more successive stratigraphic horizons are each classified as being composed dominantly of clays and/or silts, then the stratigraphic combination constitutes one unique hydrogeological semi-permeable layer.

2) semi-permeable layers #1 and #2 are, thereafter, defined *geologically* in relation to stratigraphic series (see section 4.1 and annex 3 of this report). If depths to the upper surfaces of each of the stratigraphic series in the delta are known, then the maximum and minimum elevations (ASL) of the semi-permeable layers #1 and #2 can, *hypothetically*, be determined. These elevations will be established in sections 4.2.1 and 4.2.2 for each of the semi-permeable layers concerned.

4.2.1 Semi-permeable layer #1 (clay and/or silt)

Within the bounds of the delta (seacoast and Ouallo/Dieri boundaries), 229 boreholes (project + Audibert, 1970) provide information about the existence or absence of semi-permeable layer #1.

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[25] Ref.: Audibert, 1970, document II, plate 2.

[26] Ref.: DHE, 1985, plate 3.

[27] Ref.: Golden Software Inc., SURFER - version 4, p. 3-26 and after.

Semi-permeable layer #1, composed of clay and/or silt, is identified with shallow recent sediments - Post-Nouakchottian or Actuel/Sub-Actuel. The deposition of these sediments is related to seasonal flood cycles (rainy season) and to geomorphological features existent at flood times. *Hypothetically*, the minimum elevation of the upper surface of semi-permeable layer #1 is (ASL) -2.0 meters[28]. Consequently, all piezometers going through a first layer (clay and/or silt), of which the upper surface is situated at (ASL) elevation > or = -2.0 meters, are considered to cross semi-permeable layer #1.

The histogram in figure 2 indicates the distribution of layer #1 (*clay and silt*) thicknesses, within the limits of the delta, as described above.

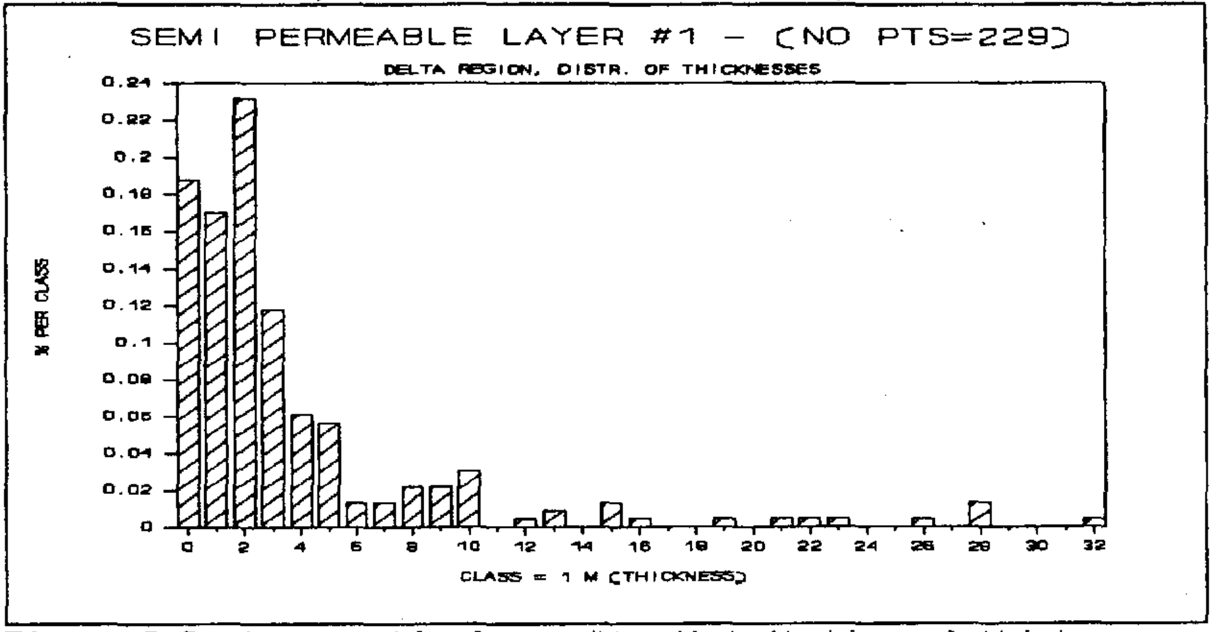

Figure 2 Semi-permeable layer #1: distribution of thicknesses

The statistics concerning the thickness of semi-permeable layer #1, composed of silts and clays, are:

NUM. PTS.	229
MIN. VAL.(m)	0.00
MAX. VAL.(m)	31.17
AVERAGE (m)	3.77
STD. DEV.(m)	5.38
MEDIAN VAL.(m)	2.00

19% of the piezometers do not cross the shallow semi-permeable layer. Consequently, discontinuous zones can be expected and are indicated on map #6 "Semi-permeable layer #1 (clay and/or silt - Probable Discontinuity Zones (dlt_ag1d)".

The average thickness of layer #1 is on the order of 3.77 meters and 76.85% of the boreholes cross this layer.

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[28] See annex 3, structure contour map of the upper surface of the Nouakchottian, corresponding to the base of the Actuel/Sub-Actuel sediments.

The median thickness of the layer is 2.0 meters. This thickness corresponds closely to the capacity of the recent sediments. The standard deviation indicates a wide range of thicknesses, up to the extreme value of 31 meters. Great thicknesses of semi-permeable layer #1 (clay and/or silt) indicate the continuous accumulation of clay and silt strata from the Nouakchottian and Post-Nouakchottian stratigraphic series. Semi-permeable layer #1 (clay and/or silt) is thickest along the banks of the Senegal River and some of its branches. On the next page, the reader will find map #5 "Semi-permeable layer #1 (clay and/or silt - isopachs (thickness) in meters (dlt_agle)". The contour line spacing is 4 meters.

Statistical comparison of the field measurements (irregular grid of the OMVS network) with thickness values extrapolated for regular grid points[29] (geostatistical calculations using the Kriging method) are:

* on the average, 0.03 meters
* standard deviation of 1.72 meters.

The standard deviation is large and indicates that the thickness of semi-permeable layer #1 (clay and/or silt) can go to zero inside the 2 meter isopach line. The 2 meter line defines the zones of probable discontinuity in the upper impermeable layer. This conclusion is especially true when their are few data points.

Probable discontinuity zone #1 is located on the edge of the delta, in the S.W. sector between the Lampsar watercourse and the Ouallo/Dieri limits, with a N.W. crescent connected to the seacoast. This zone includes the Birette and Nguinor Toundous composed of dune sand dating from the Ogolian. These sediments constituted areas not submerged during the Nouakchottian marine transgression.

Probable discontinuity zone #2 is located at the N.W. limit of the delta.

Probable discontinuity zone #3 covers Djoudj National Park. Having no data points in its interior, this zone would seem to be of mathematical origin, developed during the geostatistical treatment of the data.

Probable discontinuity zone #4 covers part of the Boundoum irrigated perimeter. The large number of data points inside this perimeter and two geological sections (see annex 4C, figures CC062D and AA062D) shed light on the causes of the heterogeneity of layer #1. Despite the calculated probability of a discontinuity, the #1 impermeable layer was observed almost everywhere within the limits of this perimeter, except at the sites of piezometers GA0059 and GA0054. The discontinuity of this impermeable layer is related to the extreme granulometric heterogeneity of the Post-Nouakchottian sediments.

Zone #5 straddles the Senegal River and covers part of the N'Thiagar irrigated perimeter, along a N.E. axis passing through the town of Rosso.

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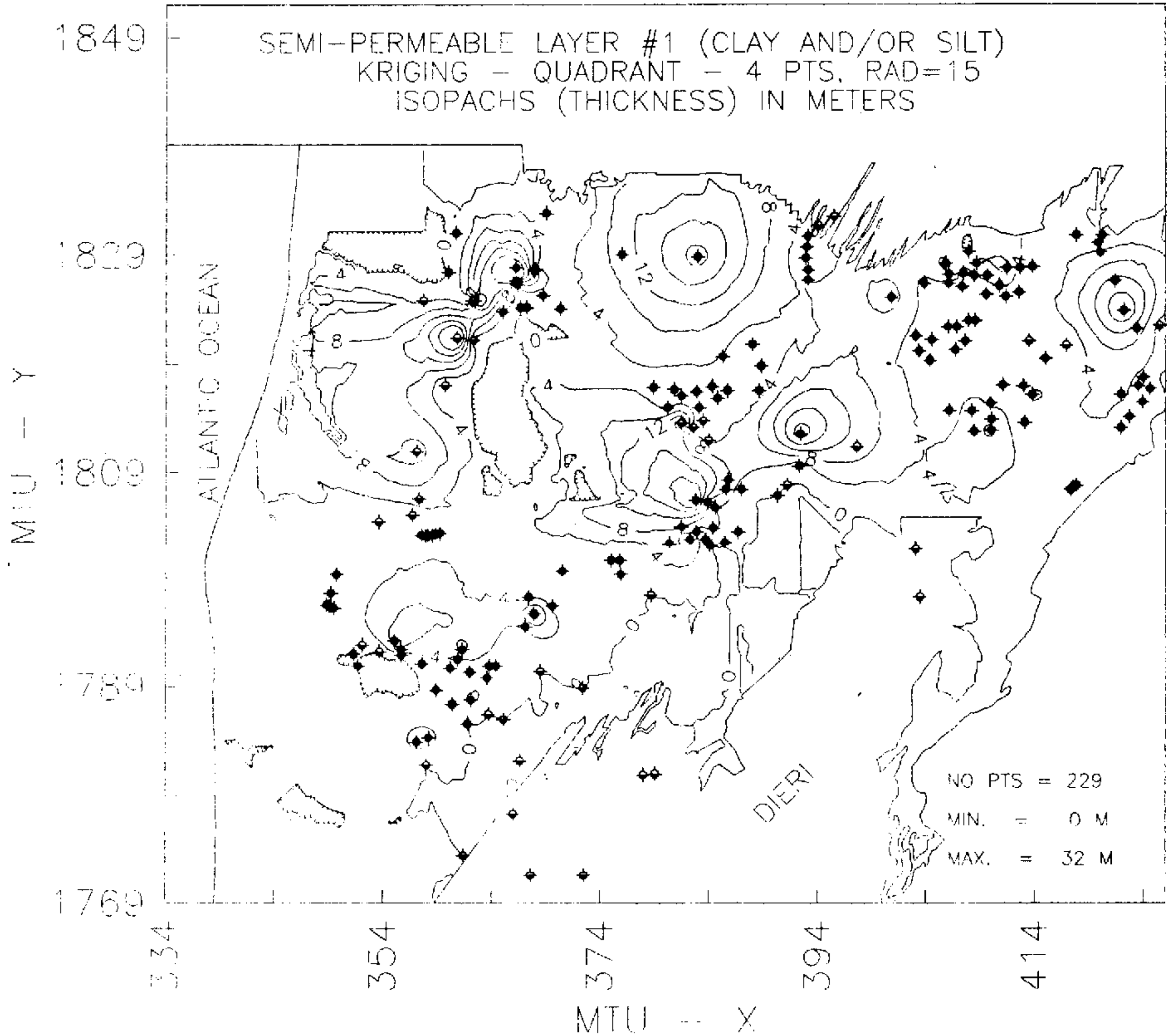
[29] Ref.: Golden Software, Inc., p. 8-40, applications of the SURFER, "Residual" function.

SENEGAL RIVER - DELTA REGION

SCALE : [scale bar] = 10 Km

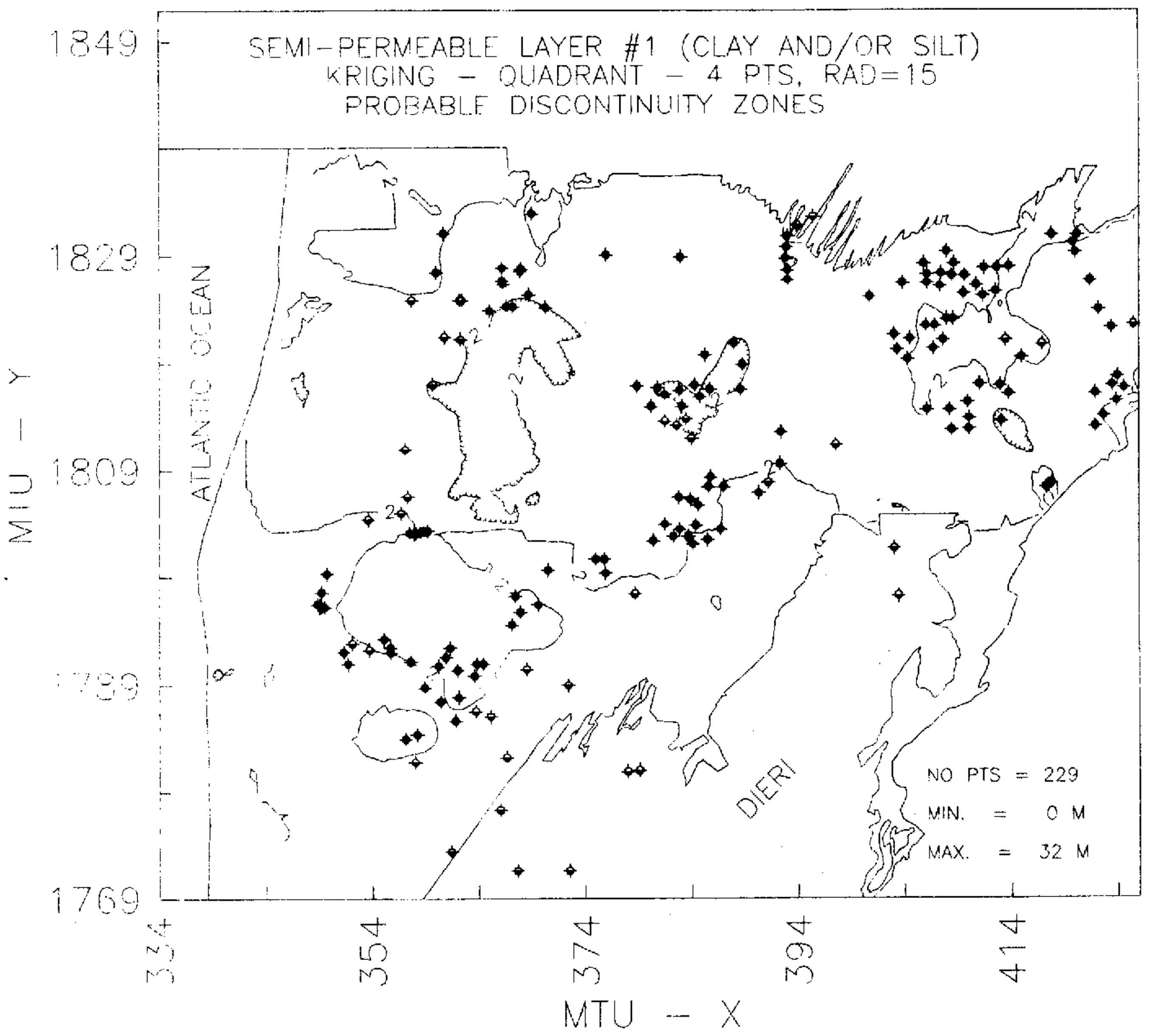
MAP Nº 5



SENEGAL RIVER – DELTA REGION

SCALE : [scale bar] = 10 Km

MAP Nº 6



4.2.2 Semi-permeable layer #2 (clay and/or silt)

Within the confines of the delta, 45 boreholes (Groundwater project + Audibert, 1970) provide information on the existence and/or absence of semi-permeable layer #2.

Semi-permeable layer #2, composed of clay and/or silt, belongs to the base of the Nouakchottian sediments and/or the summit of the Inchirian sediments. Hypothetically, the maximum and minimum elevations of the upper surface of semi-permeable layer #2 (clay and/or silt) are between -5.0 meters and -15 meters (ASL). These limiting values are based on the minimum and maximum elevations (ASL) of the upper surface of the Inchirian sediments. Determination of the geological contact elevation was made on the basis of data extracted from all the boreholes made within the confines of the delta[30].

In consequence, all piezometers passing through a layer of clay and/or silt, of which the upper surface elevation is > or = -15 meters and < or = -5 meters, are considered to cross semi-permeable layer #2. The histogram of figure 3 indicates the distribution of thicknesses of layer #2 *(clay and/or silt)* within the confines of the delta, as described above.

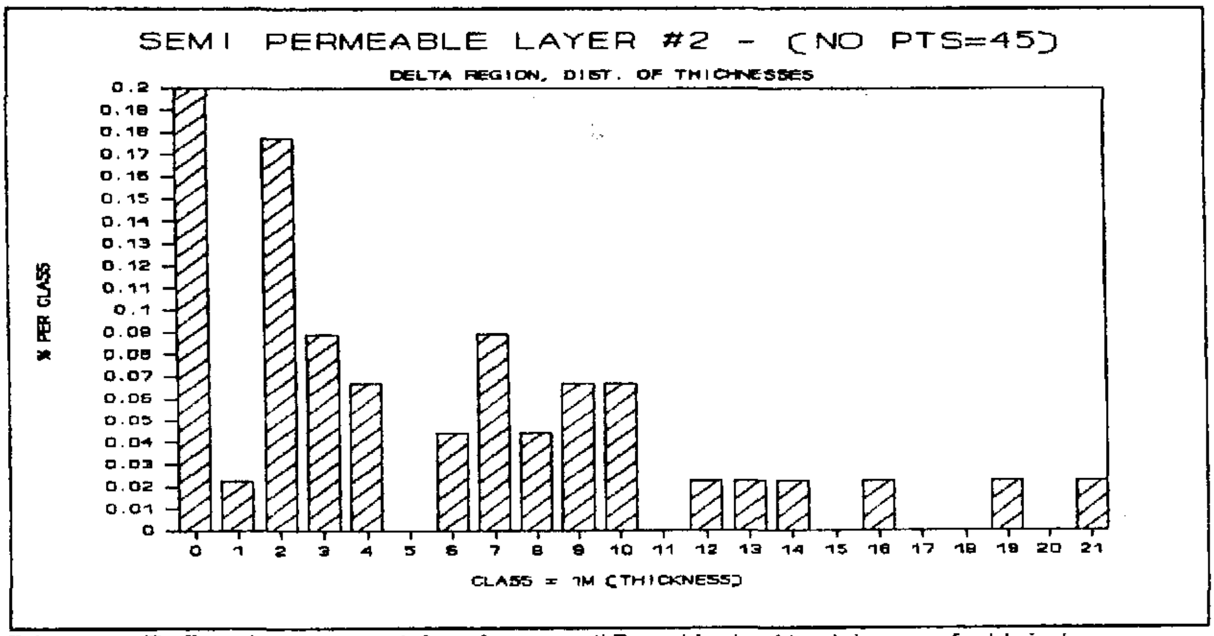


Figure 3 Semi-permeable layer #2: distribution of thicknesses

The statistics concerning the thickness of semi-permeable layer #2, composed of silts and clays are:

NUM. PTS.	45
MIN. VAL. (m)	0.00
MAX. VAL. (m)	21.00
AVERAGE (m)	5.40
STD. DEV. (m)	5.24
MEDIAN VAL. (m)	3.00

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[30] See annex #3, structure contour map of the upper surface of the Inchirian sediments.

20% of the piezometers do not cross semi-permeable layer #2. Consequently, semi-permeable layer #2 is probably discontinuous. The zones of probable discontinuity are shown on map #8.

The average thickness is about 5.4 meters.

The median thickness is about 3 meters. The standard deviation (5.24 meters) indicates a wide range of thicknesses for semi-permeable layer #2. The maximum thickness measured is 21 meters. The greatest thicknesses of semi-permeable layer #2 (clay and/or silt) are located along the banks of the Senegal River and some of its connected watercourses. The reader will find, on the next page, map #7 "Semi-permeable layer #2 (clay and/or silt) - Isopachs (thicknesses) in meters (dlt_ag2e)". The isopach contour lines are spaced at 4 meters. The locations of the thickest layers of clays and silts coincide with the depressions in the upper surface of the Inchirian sediments (see annex #3, map "structure contour map of the upper surface of the Inchirian sediments") and also correspond to the current course of the Senegal River.

The statistical comparison of the field measurements (irregular grid of the OMVS network) with those extrapolated for a set of regular grid points[31] (geostatistical calculations using the Kriging method) are:

* on the average, 0.30 meters,
* standard deviation of 1.23 meters.

The standard deviation is large and indicates that the thickness of semi-permeable layer #2 (clay and/or silt) can go to zero inside the 1.5 meter isopach curve. The 2 meter curve indicates the zones of probable discontinuity of impermeable layer #2 (see map #8 "Semi-permeable layer #2 (clay and/or silt) - Probable discontinuity zones (dlt_ag2d)").

There are two zones of probable discontinuity:

Zone #1 is situated in the North of the delta and zone #2 to the west of Lac de Guiers. Some small discontinuity zones are located along the N-S stretch of the Senegal River upstream of Diama Dam.

Areas of superposition of zones of probable discontinuity of impermeable layers #1 and #2 are few and limited:

1) to the North of the town of Keur Macène,

2) N.W. of Lac de Guiers in the zone where Ancient and Middle Quaternary sediments are very shallow.

4.2.3 Aquifer

The characteristics of semi-permeable layers #1 and #2 (vertical position, thickness and discontinuity) reveal the existence of one single aquifer compartmentalized into two juxtaposed reservoirs: upper and lower. The upper compartment is confined or unconfined depending on whether semi-permeable layer #1 (clay and/or silt) is continuous or not. The lower compartment is separated from the upper compartment by discontinuous, semi-permeable layer #2 (clay and/or silt). The two reservoirs of the aquifer should be, consequently, hydraulically linked. At the same time, the lateral

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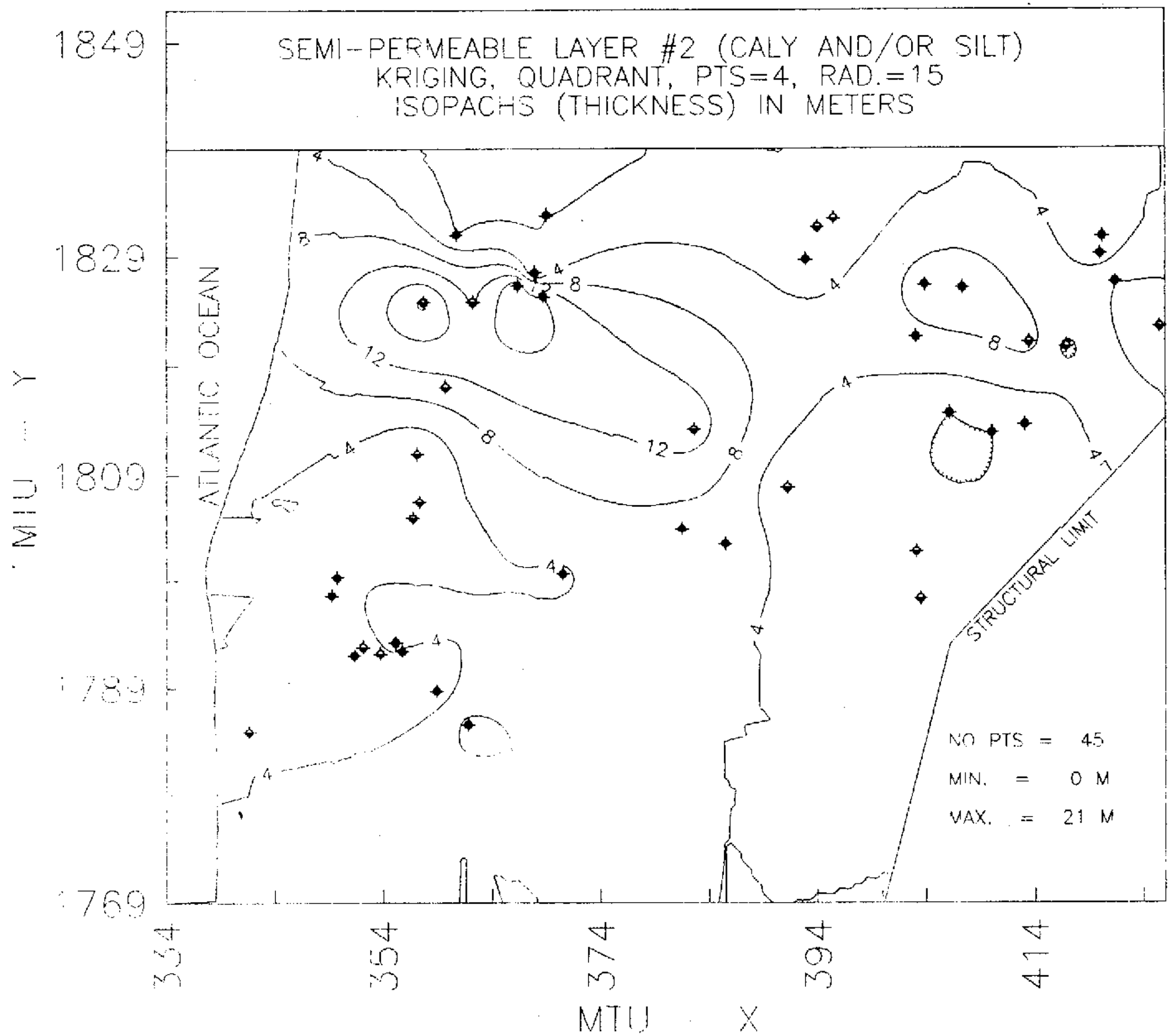
[31] Ref.: Golden Software, Inc., p. 8-40, applications of the SURFER "Residual" function.

SENEGAL RIVER – DELTA REGION

SCALE : = 10 Km

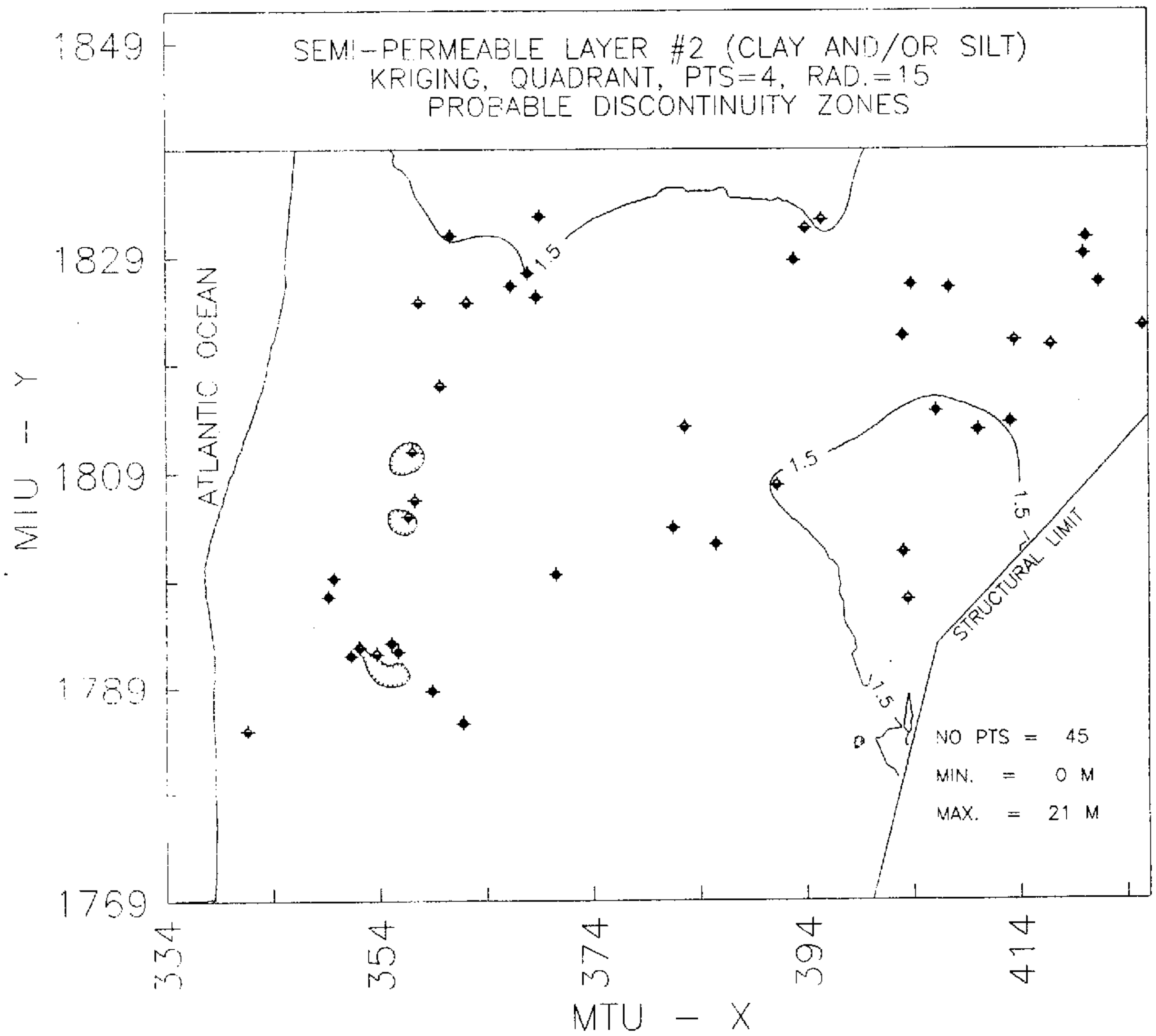
MAP Nº 7



SENEGAL RIVER — DELTA REGION

SCALE : = 10 Km

MAP Nº 8



extension of semi-permeable layers #1 and #2 is significant within the confines of the delta.

This schematic description of the aquifer modifies the initial hypothesis of two distinct aquifers (see section 4.1).

Within the confines of the delta, the aquifer situation is one aquifer compartmentalized into two juxtaposed reservoirs, linked across their mutual boundary.

Following this section, the reader will find map #9 "Aquifer - structural contours of the upper surface (m ASL) (dlt_aq1t)". In the zones where semi-permeable layer #1 (clay and/or silt) exists, the upper surface of the aquifer corresponds to the base of layer #1; in the zones where semi-permeable layer #1 (clay and/or silt) is considered to be probably discontinuous, the upper surface of the reservoir corresponds to the topographic elevation of the piezometer site.

The statistical comparison of the field measurements (irregular grid of the OMVS network) with those extrapolated for regular grid points[32] (geostatistical calculations using the Kriging method) are:

* on the average, 0.02 meters,
* standard deviation of 1.82 meters.

The standard deviation is large and indicates that the aquifer may be considered unconfined within the 2 meter contour line, i.e., with an unrestrained water table and an unsaturated zone.

Following this section, the reader will find map #10 "Aquifer - upper compartment - structure contours of its lower surface (m ASL) (dlt_aq1b)". The elevation of the periphery varies between -8 and -12 meters, sometimes attaining values >-20 meters. These particular zones correspond to zones of discontinuity in the clay/silt layer #2 (see section 4.2.2).

Following this section, the reader will find map #11 "Aquifer - upper compartment - isopachs (thicknesses) in meters (dlt_aq1e)" which indicates the zones where the aquifer thickness is zero. These zones are located:

1) near the irrigated perimeter at Debi, where, as previously mentioned, there are shallow Inchirian sediments (see section 4.2.2),

2) between the irrigated perimeters at Boundoum and Grande Digue Tellel Kassak, to the West of the Lampsar,

3) near Kheun, midway between the towns of Keur Macène and Rosso, along the Senegal River.

These three zones are perfectly aligned with the zones of maximum thickness of clay/silt layer #1.

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[32] Ref.: Golden Software, Inc., p. 8-40, applications of the SURFER "Residual" function.

In conclusion, the aquifer is characterized:

* by an upper compartment *structurally* confined or unconfined, depending on the existence or absence of semi-permeable layer #1 (clay and/or silt),
* by an upper compartment *hydrogeologically* confined or unconfined depending on whether the elevation (ASL) of the water table is above or below the elevation (ASL) of the aquifer's upper surface. The nature of this aquifer may possibly change seasonally during the annual cycle.

* the upper compartment of the aquifer has a relatively homogenous granulometry but is discontinuous in thickness (thickness of the compartment is sometimes zero).

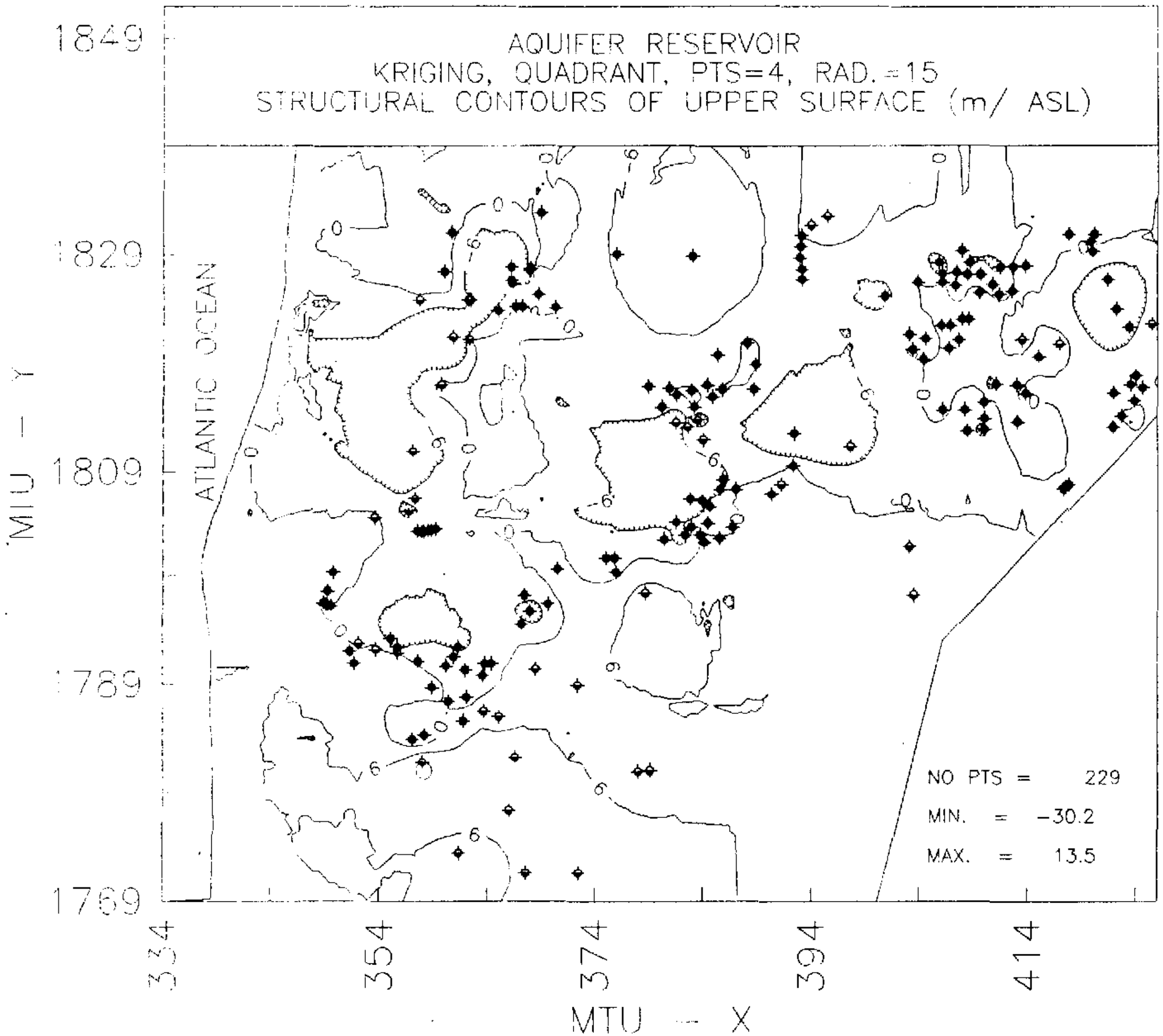
* the thickness of the upper compartment varies from 0 to 12 meters and is principally located in Nouakchottian sediments, sometimes in the upper parts of the Inchirian sediments,

* the thickness of the lower compartment has not been determined by the project.

SENEGAL RIVER – DELTA REGION

SCALE : = 10 Km

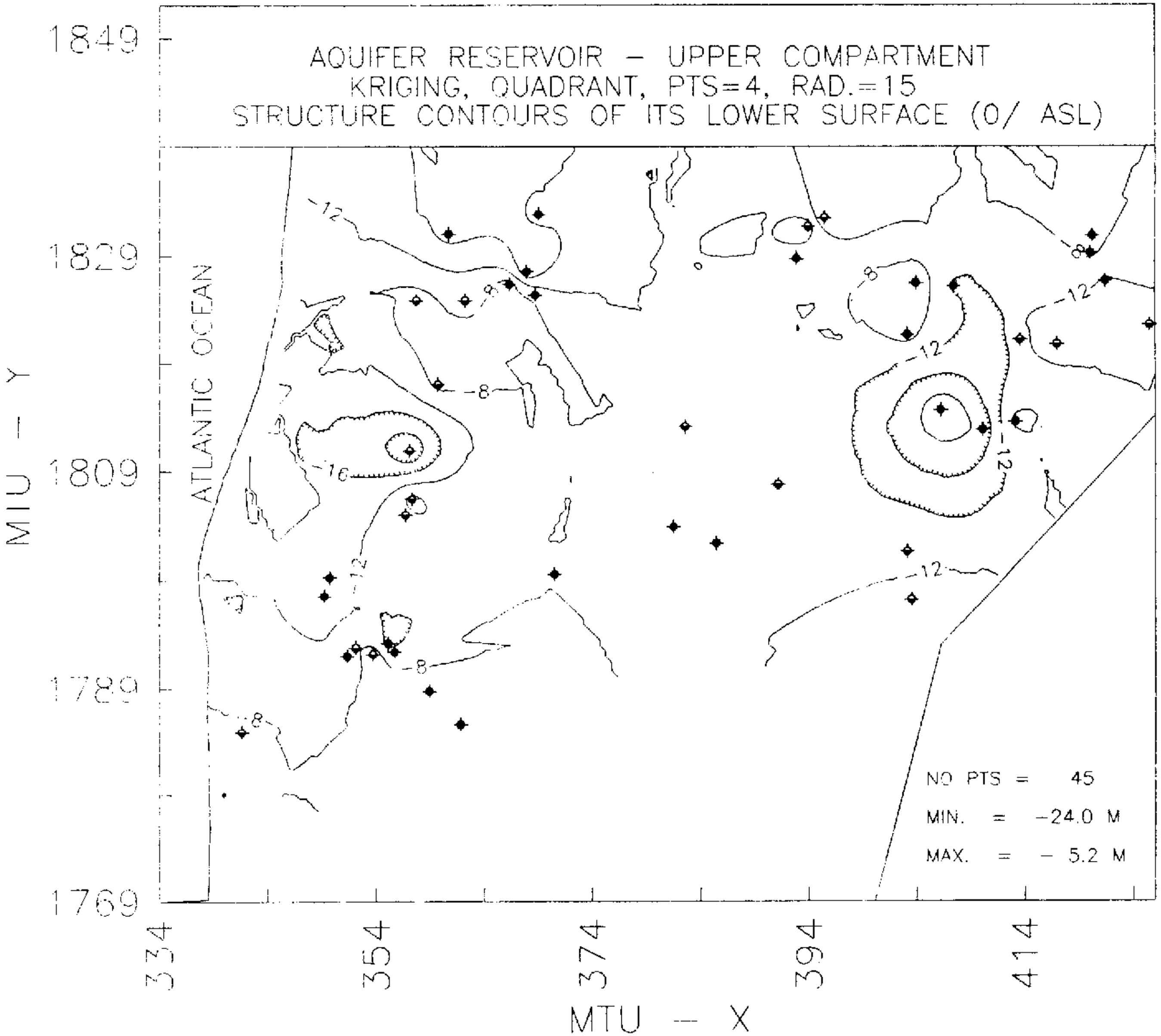
MAP Nº 9



SENEGAL RIVER - DELTA REGION

SCALE : = 10 Km

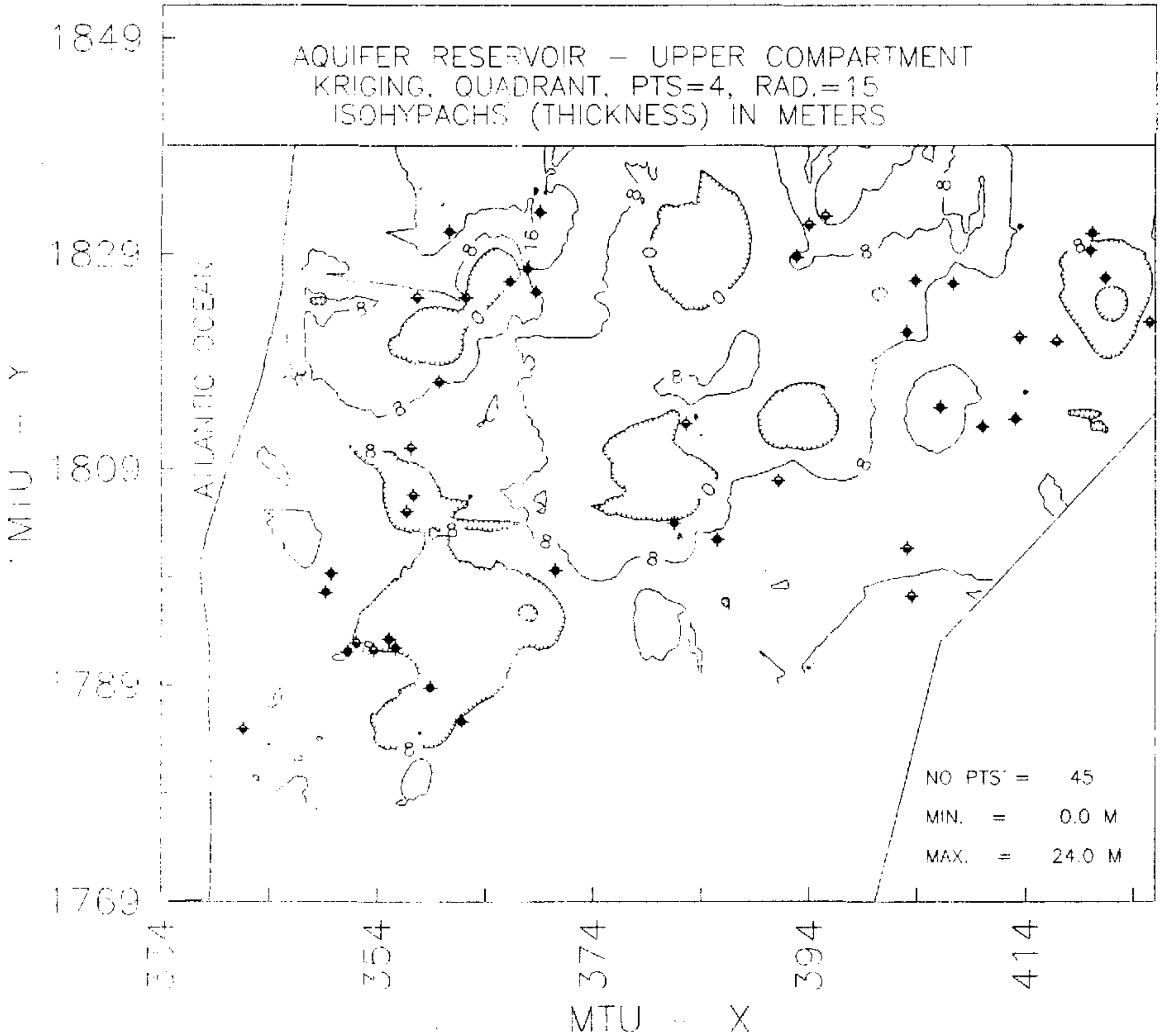
MAP Nº 10



SENEGAL RIVER – DELTA REGION

SCALE : ———— = 10 Km

MAP Nº 11



5 DELTA - HYDROGEOLOGICAL CHARACTERISTICS

5.1 Structural hydraulic parameters

5.1.1 Hydraulic conductivity measurements at descending levels

Each of the piezometers constructed by the project was first developed for two hours. Upon recovery of the static water level, a hydraulic conductivity test (KK) was performed, by the dropping water level method[33] (slug test). The interpretation method used was that of Hvorslev[34].

Use of this method does not depend on the shape of the reservoir being tested. Unsuitable for use in plastic clays (rare within the confines of the delta and always at the surface)[35] it takes into account the shape and dimensions of the piezometer intake (length of the intake systematically = 1 meter).

This method is suitable for values of transmissivity less than 10^{-3} m^2/sec. When transmissivity values are close to or greater than this limit, the drop in the water level is rapid (often instant) and practically unmeasurable. In such cases, only pumping tests will provide the hydraulic conductivity values needed.

Within the delta limits, the project performed 211 hydraulic conductivity tests by the dropping water level method. The notion of an aquifer in two compartments led to the classification of the test results into two groups based on the depth of the piezometer intake:

* upper compartment: depth of the intake less than 13 meters,

* lower compartment: depth of the intake greater than 13 meters.

Figures 4 and 5 indicate the logarithmic distribution of the hydraulic conductivity values by geological formation; upper and lower aquifer compartments, respectively.

Annex 5 includes the lists of hydraulic conductivity values for each group (upper and lower aquifer compartments).

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[33] Ref: Société d'Energie de la Baie James, March 1978.

[34] Ref: FREEZE and CHERRY, 1979, p. 340-341.

[35] Ref.: Audibert, 1970, document IV, p. 10.

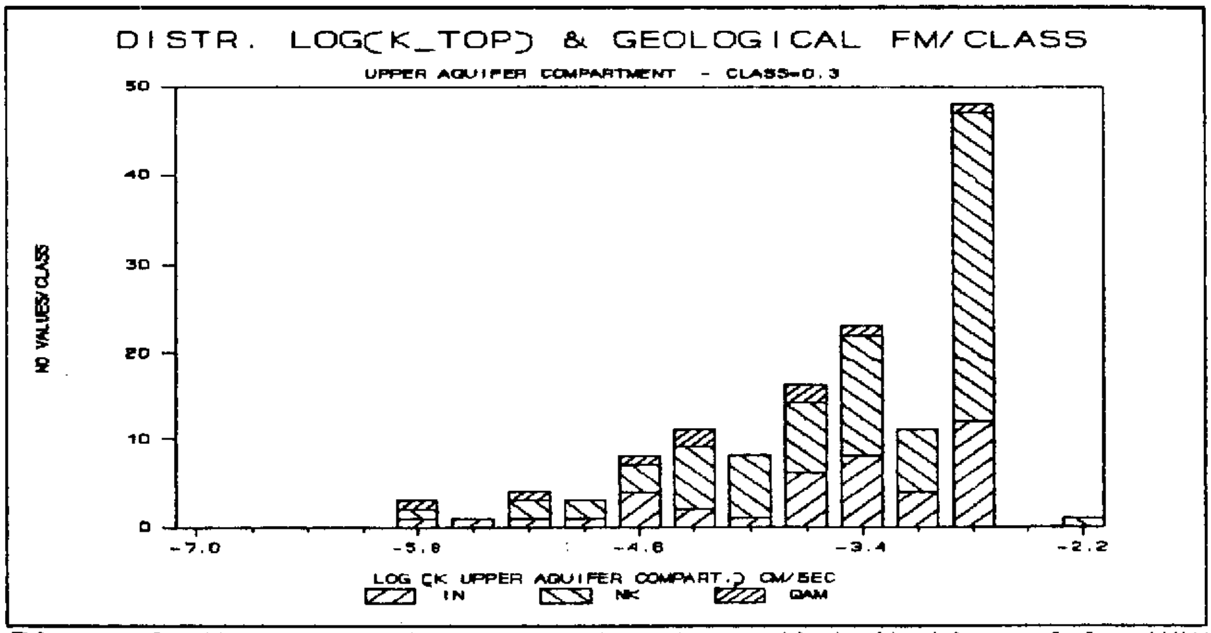


Figure 4 Upper aquifer compartment - distribution of log(KK) vs. geological formation

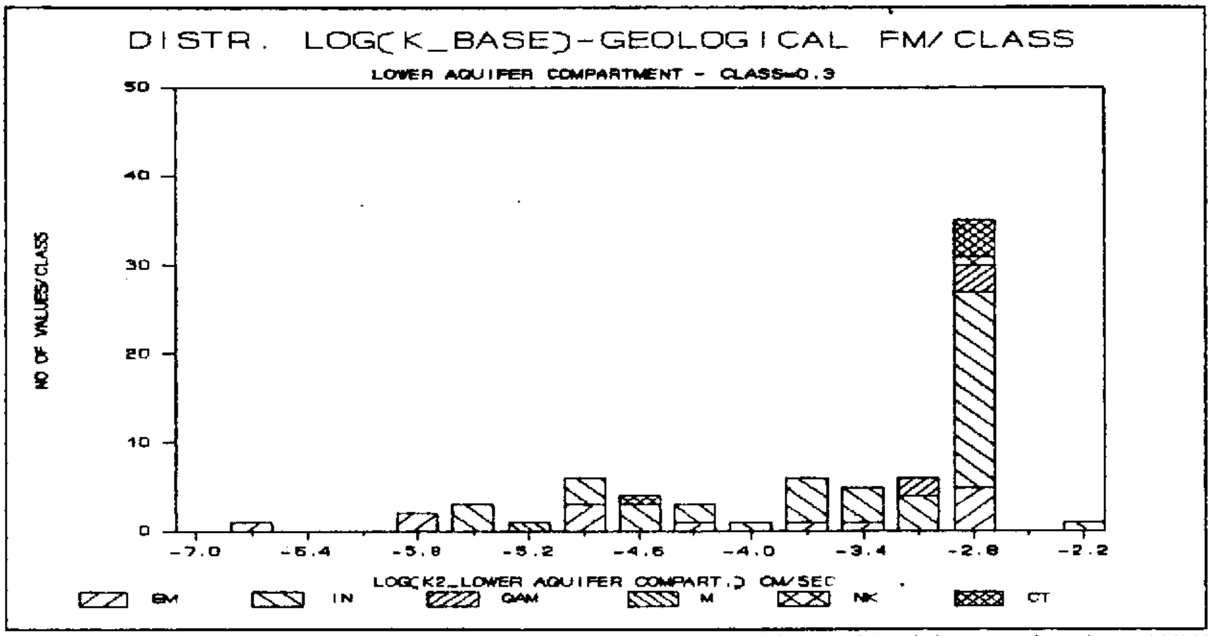


Figure 5 Lower aquifer compartment - distribution of log(KK) vs. geological formation

UPPER PART OF AQUIFER = INTAKE DEPTH < 13.0 M

STATISTICS	INTAKE DEPTH	K(Cm/s)	LOG(KK)
NUMBER	137	137	137
MIN.	4.00	8.50E-07	-6.07
MAX.	13.00	3.40E-03	-2.47
MEDIAN	-	3.00E-4	-3.52

LOWER PART OF AQUIFER = INTAKE DEPTH > 13.0 M

STATISTICS	INTAKE DEPTH	K(Cm/s)	LOG(KK)
NUMBER	74	74	74
MIN	13.0	1.8E-07	-6.74
MAX	49.2	5.5E-03	-2.26
MEDIAN	-	6.9E-04	-3.15

For both cases - upper and lower aquifer compartments, we see that:

1) the range of hydraulic conductivity values is large ($1*10^{-6}$ cm/s to $>1*10^{-3}$ cm/s) reflecting the heterogeneity of the tested sediments,

2) all the geological formations are well represented in each of the classes of log(kk) except for the TC formation for which all the conductivity values are in the upper range ($>1*10^{-3}$ cm/s) (see figure 5).

Seven piezometers tap this formation, a substratum of Quaternary sediments. All are located North of the Senegal River, near Rosso (see annex 3, map of Tertiary sediments - structure contours of the upper surface and relevant boreholes.

Figures 4 and 5 indicate a predominant class (log kk = -2.8). This class corresponds to the upper limit for which the dropping water level method should be used to measure hydraulic conductivity. Beyond this limit the rate of drop is too rapid to interpret accurately. In these situations, a hydraulic conductivity value of $>1*10^{-3}$ cm/s was attributed. Such was the case for about 40% of the tests made. If the distribution of hydraulic conductivity values is log-normal, as is often the case (Freeze and Cherry, 1975), then the median value can be determined. Assuming that the hydraulic conductivity values are distributed symmetrically about the median, the standard deviation can be estimated. The value of the standard deviation is estimated such that the values "median +/- standard deviation" include 2/3 of all the hydraulic conductivity values measured.

This estimation was made for the upper and lower aquifer compartments and the two combined. The results are:

aquifer	number	median cm/s	std.dev.
upper	137	$3.0*10^{-4}$	$2.7*10^{-4}$
lower	74	$6.9*10^{-4}$	$6.5*10^{-4}$
combined	211	$4.4*10^{-4}$	$4.0*10^{-4}$

The ranges of values between the limits - "median value +/- standard deviation" - overlap for the two compartments and make any differentiation between the hydraulic conductivities of the compartments difficult, especially if the number of samples is small. In other words, what is the probability that the difference between the median values for the two compartments is due to chance rather than to a real difference in the hydraulic conductivities caused by the geological natures of the upper and lower compartments?

To answer this question, we make the hypothesis that the median hydraulic conductivity values correspond to the average values. In that case, the distribution of values is log-normal and the standard deviation of the differences between the average values of each of the compartments is given by the following formula[36]:

$$\sigma_D = ((\sigma_s^2/n_s)+(\sigma_i^2/n_i))^{1/2}$$

where:

σ_s = standard deviation of the hydraulic conductivity values for the upper compartment,

σ_i = standard deviation of the hydraulic conductivity values for the lower compartment,

n_s = number of hydraulic conductivity values for the aquifer's upper compartment,

n_i = number of hydraulic conductivity values for the aquifer's lower compartment.

The value of σ_D which results from use of the formula with the median hydraulic conductivity values is $7.9*10^{-5}$ cm/s. The difference between the median hydraulic conductivity values ($6.9*10^{-4} - 3.0*10^{-4} = 3.9*10^{-4}$) is 4.9 times greater than the value of σ_D.

Consequently, the lower compartment sediments are twice as permeable, on the average, as the upper compartment sediments. Even if the statistical difference is clear, it is good to consider the criteria used in the field for stopping the drilling work: the determination of the most permeable horizon over the depths considered for the drilling programs - shallow (<15 meters) and deep (> 15 meters and < 65 meters). The probability of encountering a more permeable horizon is greater for the deep boreholes than for the shallow boreholes.

The range of values between these limits - "median value +/- standard deviation" - coincides with the low values of hydraulic conductivity characteristic of semi-permeable aquifer formations (fine sand and silt) (ref.: Bear, Zaslavsky and Irmy, 1968). This coincides perfectly with the results for the Quaternary sediments found in the confines of the delta during construction of the OMVS piezometric network. We propose the values for the combined compartments: $4.4*10^{-4}$ cm/s (average) and $4.0*10^{-4}$ cm/s (standard deviation).

[36] Arkin and Colton, 1970.

5.1.2 Pumping test results

Within the confines of the delta, the project performed 6 pumping tests (DA001, DA032, DA083, GA0036, GA0255, GA0264). The pumping time was limited to 48 hours and the time of observation of the water table rise was also limited to 48 hours. The reader will find the locations of the sites on map #12 "Pumping test site locations (dlt_locq)". The hydraulic parameters of the aquifers tested are listed in the table below. They are shown in the following order[37], specific discharge (Qc), specific critical drawdown (Dc), coefficient of transmissivity (T), aquifer thickness (E), horizontal hydraulic conductivity (KQ), coefficient of storage (S), drainability factor (L), the coefficient of drainability (c) and vertical hydraulic conductivity (Kv).

Table #4: Aquifer hydraulic parameters

PARAM.	UNITS	DA001	DA032	DA083	GA0036	GA0255	GA0264
Qc	m3/hr	14.0	ND	>10.0	ND	ND	12.0
Dc	m	1.68	ND	>3.0	ND	ND	4.0
T	m2/s	2.50E-03	2.00E-03	2.00E-02	NI	NI	1.00E-03
E	m	>21	20.0	7.0	>5	>19	>20
KQ	m/s	1.00E-04	1.00E-04	2.86E-03	NI	NI	4.00E-05
S	none	1.00E-04	4.00E-04	NA	NI	NI	7.00E-04
L	m	760	579	NA	NI	NI	109
c	days	2600	1889	NA	NI	NI	121
Kv	m/s	9.00E-09	6.00E-09	NA	NI	NI	4.00E-07
COMPARTMENT		LOWER	LOWER	LOWER	LOWER	LOWER	LOWER
INTERPRETATION		WALTON[38]	WALTON	JACOB[39]	-	-	WALTON

ND = not done
NA = not applicable
NI = not interpretable

The observation piezometers for the DA083 pumping station did not show a response during the test, thus the interpretation is not rigorous.

The GA0036 and GA0255 pumping stations emptied after a few minutes of pumping, thus halting the tests.

In this table, the vertical hydraulic conductivities. the coefficients of drainability and the drainability factors, show the effect of the semi-permeable interlaminate layer (semi-permeable layer #2).

The pumping tests performed by the project did not test the upper compartment. However, SOGREAH et al. did test it and they concluded[40]:

"the aquifer tests showed that:

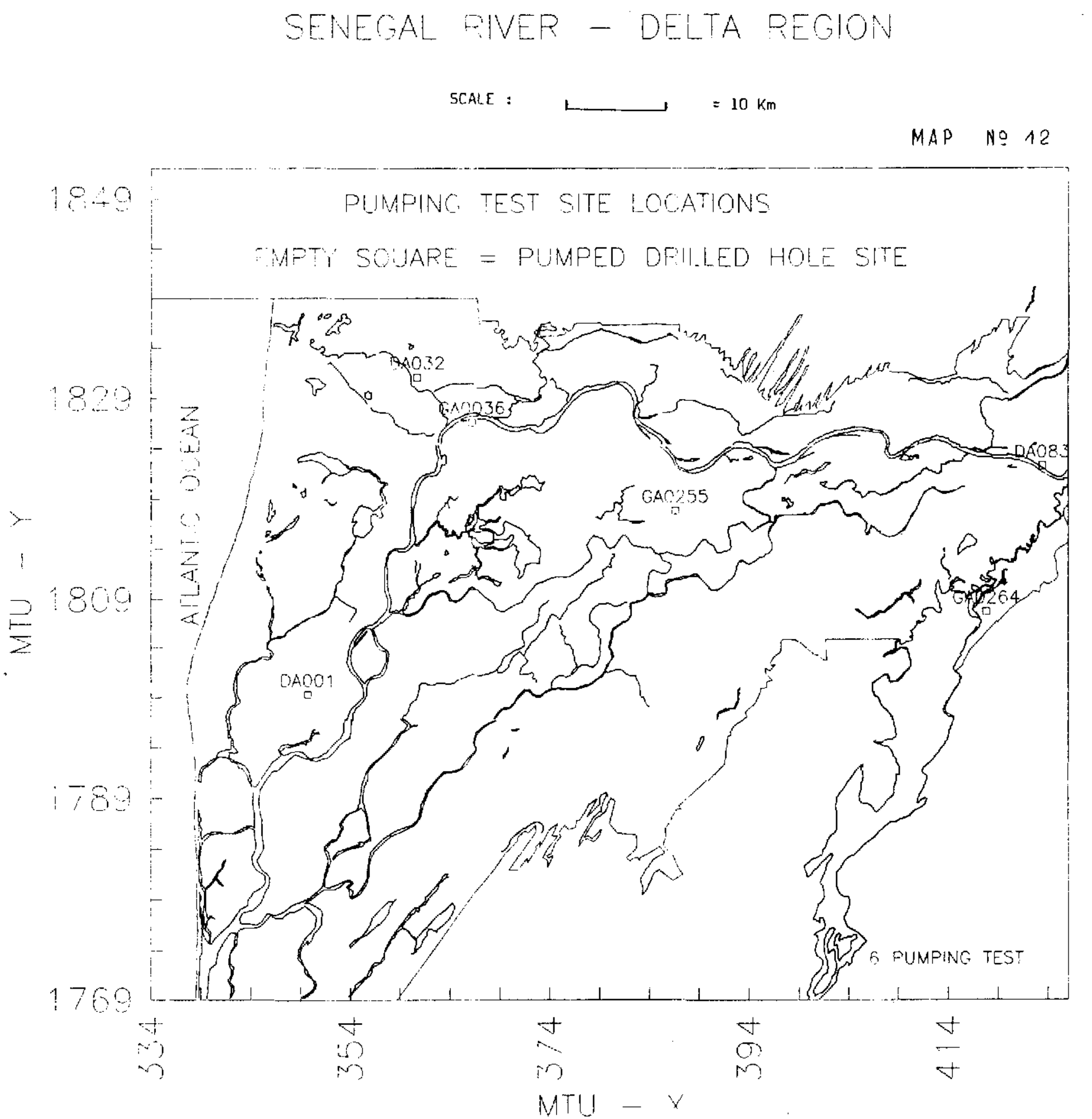
* the so-called "upper" aquifer, in principle, between the elevations (ASL) -10 m and -14 m, is poorly isolated and is partially linked to the lower aquifer. Its transmissivity is on the order of 10^{-3} m^2/s ($K=2*10^{-4}$ m/s).

[37] For a rigorous, scientific definition, see Castany, 1977.

[38] Ref.: Kruseman, 1979, p. 81.

[39] Ref.: Kruseman, 1979, p. 59.

[40] Ref.:SOGREAH et al., 1978, p.58.



SENEGAL RIVER - DELTA REGION
SCALE : = 10 Km
MAP Nº 12
PUMPING TEST SITE LOCATIONS
EMPTY SQUARE = PUMPED DRILLED HOLE SITE
ATLANTIC OCEAN
DA032
GA0036
DA083
GA0255
DA001
6 PUMPING TEST
1849
1829
1809
1789
1769
MTU - Y
334
354
374
394
414
MTU - X

* the "lower" aquifer, between about -16 m and -30 m, is situated in a terrain of very homogenous permeability. Its transmissivity is on the order of 10^{-2} m^2/s ($K=6*10^{-4}$ m/s).

* the two aquifers are recharged by the Senegal River which we can consider, without great error, as a linear East-West recharge situated about 300 m ...

* the two aquifers behave as confined aquifers, the coefficient of storage of the lower aquifer being on the order of $8*10^{-4}$."

The lower compartment, submitted to pumping tests at six distinct sites, contains a semi-confined aquifer which is weakly recharged by vertical drainage, as is shown by the large values for the drainability factor (L) for the DA001 and DA032 sites. This aquifer belongs to Inchirian sediments (see the structure contour map of the Inchirian in annex 3).

The substratum (Tertiary stratigraphic series) was not tested.

The hydraulic conductivity values obtained with the slug tests (KK) are one order of magnitude smaller than the values obtained with the pumping tests (KQ). This is surprising since the slug tests characterize strata (generally 1 meter high along the length of the piezometer intake) chosen for their large apparent permeability (see the drilling halt criteria) whereas the pumping tests (48 hours) characterize a much larger volume of sediment (radius of 100 meters around the well point). It would be logical to have the opposite results, i.e., values of KK > KQ.

Despite the difference of one order of magnitude, we feel that the average hydraulic conductivity value, determined by statistical analysis of the values calculated from the slug test results, is the value to use in calculations for the following reasons:

* a large number of slug tests were made (271),

* the spatial distribution of the slug tests in the delta is good,
* the vertical distribution of the tests (shallow and deep boreholes) represents both aquifer compartments,

* the hydraulic conductivity values interpreted from the test results reflect the geological nature of the sediments which are tapped by the OMVS piezometric network.

Therefore, the average hydraulic conductivity value of $K=4.4*10^{-4}$ cm/s will be used in later calculations.

The values of (S) determined from the pumping tests are on the order of 10^{-4} (dimensionless). These values are characteristic of confined aquifers.

Theoretical[41] values of (S) for unconfined water tables are:

gravel	.23 to .25
sand	.23 to .28
silt	.08
clay	.03
dunes	.38

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[41] Ref.: Todd. 1980.

The geometric description of the delta aquifer (see chapter 4), in relation to its principal structural hydraulic parameters (K, T, S and Kv) is presented below.

The hydraulic conductivity values mentioned in this description originate from pumping tests (KQ=cm/s), hydraulic conductivity test (KK=cm/s) and granulometric analyses (KB=cm/s).

0 ----------------------		surface
10^{-5} < KB < 10^{-7} cm/s		semi-permeable layer #1
4/5 m ------------------		*AQUIFER UPPER COMPARTMENT*
KK hor. v. median	= $3.0 * 10^{-4}$ cm/s	
KK std. deviation	= $2.7 * 10^{-4}$ cm/s	
KQ hor. Sogreah	= $2.0 * 10^{-2}$ cm/s	
T Sogreah	= 10^{-3} m^2/sec	
S	= $8.0 * 10^{-4}$	
15/18 m ----------------		
		semi-permeable layer #2
KQ vert.	= 10^{-7} to 10^{-9} m/sec	
19/30 -------------------		*AQUIFER LOWER COMPARTMENT*
KK hor. v. median	= $6.9 * 10^{-4}$ cm/s	
KK std. deviation	= $6.5 * 10^{-4}$ cm/s	
KQ hor.	= 10^{-3} to 10^{-1} cm/s	
T	= 10^{-2} to 10^{-3} m^2/sec	
S	= 10^{-4}	
40/50 m ----------------		
		substratum

5.2 Geohydrochemistry

For the entire delta, a total of 89 samples of groundwater (74) and surface water (15) were analyzed by the National soil and water analysis laboratory (Laboratoire National d'Analyses des Sols et de l'Eau - LANASOL), operated by SONADER[42] in Nouakchott, for major cations and anions, as well as nitrites and nitrates.

Analyses results (tables and graphs) are presented in annex 6. The tables in this annex include complimentary information as well, such as sample depth, nearby watercourses (name and distance) and the usual anions/cations content report. For reference, the average chemical composition of sea water, as proposed by ORSTOM[43], is also given.

Additional samples were taken at some sites as part of the pumping tests.

The laboratory results were analyzed to determine the existence of:

1) a vertical chemical stratification as a function of depth,

2) chemically differentiated zones parallel to nearby watercourses.

The chemical content of the groundwater samples does not vary regularly as a function of sample depth, or the distance of the sample site from the nearest watercourse. The reader may refer to the graphs in annex 6 for illustrations. Variation in Cl content with depth of the piezometer intake is shown in figure #2 of the annex, and with horizontal distance from the sample site to the nearest watercourse is shown in figure #1. The Cl content varies extremely irregularly with depth and horizontal distance. This indicates an aquifer which is very heterogenous, both vertically and horizontally, and of a discontinuous, lenticular nature.

However, the variations of typical ion concentration ratios (see tables, annex 6) show that the ratios increase with depth, weakly for the Cl-/Na+, Mg++/Ca++ and Na+/K+ relationships; more significantly for the (Na+K)/(Ca+Mg) and Cl-/SO4-- relationships.

The best-fit linear equations describing the changes with depth are:

ratios	equations (depth = m)	remarks
Cl^-/SO_4^{--}	y = 1.04779 (depth) + 13.2593	significant
Cl^-/Na^+	y = 0.0034180 (depth) + 1.7546	weak
Mg^{++}/Ca^{++}	y = 0.0111616 (depth) + 1.13089	weak
Na^+/K^+	y = 0.0086544 (depth) + 16.6412	weak
(Na+K)/(Ca+Mg)	y = 0.0523016 (depth) + 2.99517	significant

A vertical chemical stratification is also identified. Figure 6 indicates the S.A.R. (sodium adsorption ratio) distribution by class (see section 5.2.2.) for the aquifer upper compartment (water intake < 13 m deep) and lower compartment (water intake > 13 m deep).

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[42] SONADER = Société Nationale pour le Développement Rural.

[43] Ref.: SAOS, 1985, p. 22, table 5.

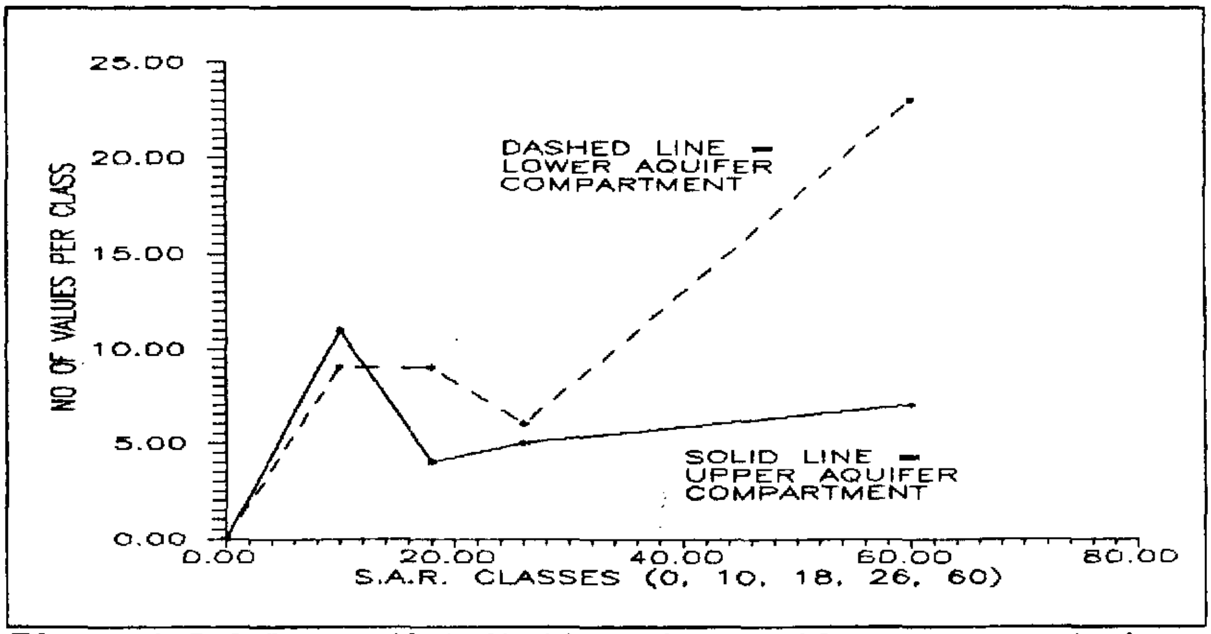

Figure 6 S.A.R. - distribution for aquifer upper and lower compartments

The variation of the typical ion concentration ratios (see tables, annex 6) also show that the ratios vary with distance from the sample site to the nearest watercourse: decrease for the ratios Mg++/Ca++, (Na+K)/(Ca+Mg) and Cl-/SO4--; increase for the ratios Cl-/Na+ and Na+/K+.

The best-fit linear equations for the changes with distance are:

ratios	equations (dist. = km)	remarks
Cl-/SO4--	y = -2.87949 (dist.) + 42.0159	decrease
Cl-/Na+	y = 0.0609257 (dist.) + 1.69932	increase
Mg++/Ca++	y = -0.0630896 (dist.) + 1.50594	decrease
Na+/K+	y = 0.923929 (dist.) + 16.5533	increase
(Na+K)/(Ca+Mg)	y = - 0.175714 (dist.) + 4.49836	decrease

The reader should understand that these equations are not precise but are merely analytical tools.

5.2.1 Geohydrochemical facies

The geohydrochemical facies of the groundwater are essentially of the sodium chloride and potassium chloride types (72/74) with a few exceptions (1/74 - calcium and magnesium bicarbonate; 1/74 - sodium sulfate). This water is of marine origin.

Anion/cation content variation is insignificant between multiple samples analyzed for the same site.

The geohydrochemical facies for surface water are principally of the sodium chloride and potassium chloride types (11/15) with a few exceptions (3/15 -calcium and magnesium bicarbonate; 1/15 - sodium sulfate).

The locations of water samples which do not fit the geohydrochemical facies typical for the region are shown on map #13 "Water analyses of non sodium chloride type (sw_gwchm)" .

5.2.2 S.A.R. - Sodium adsorption ratio

The map #14 "S.A.R. - sodium adsorption ratio - period 1987-1988 (sar)", indicating the S.A.R. isovalues of the groundwater, was drawn using the following classes[44]:

code	class limits	number samples/class surface	groundwater
S1	0 < SAR < 10	15/15	20/74
S2	10 < SAR < 18	-	13/74
S3	18 < SAR < 26	-	11/74
S4	SAR > 26	-	30/74

The S1 and S2 class water samples of generally come from village wells, rarely from piezometers, located:

* along a NE-SW axis, parallel to the Ouallo/Dieri limits in the south of the delta,

* near Djoudj national park, south of the Debi perimeter,

* along a N-S axis passing through Lac de Guiers and the town of Rosso, and coincident with the unconfined aquifer zone.

The S3 and S4 class water samples come from the zones where the large irrigated perimeters have been developed, except for the CSS and the M'pourie perimeters which are located in the eastern part of the delta in the unconfined aquifer zone. The perimeters are located in heavy soils of the impermeable clay/silt layer #1.

All the surface water samples are class S1. We note, however, higher S.A.R. values for the surface waters from the sloughs (Lampsar, Djeuss and Gorom). This reflects their status of natural drains receiving salt loaded water from fields where the soil is leached before planting.

5.2.3 T.D.S. - Total dissolved solids

The map #15 "T.D.S. - Total dissolved solids (mg/l), laboratory values (tds)" indicating the T.D.S. isovalues of the delta groundwater, was drawn using the following classes[45]:

limits mg/l	class	number of samples surface	groundwater
0 < TDS < 1,000	fresh	11/15	8/74
1,000 < TDS < 10,000	brackish	4/15	32/74
10,000 < TDS < 100,000	saline	-	34/74
100,000 < TDS	brine	-	0/74

The fresh and brackish samples generally come from village wells, rarely from piezometers, located:

* along a NE-SW axis, parallel to the Ouallo/Dieri limits in the south of the delta,

* near Djoudj national park, south of the Debi perimeter,

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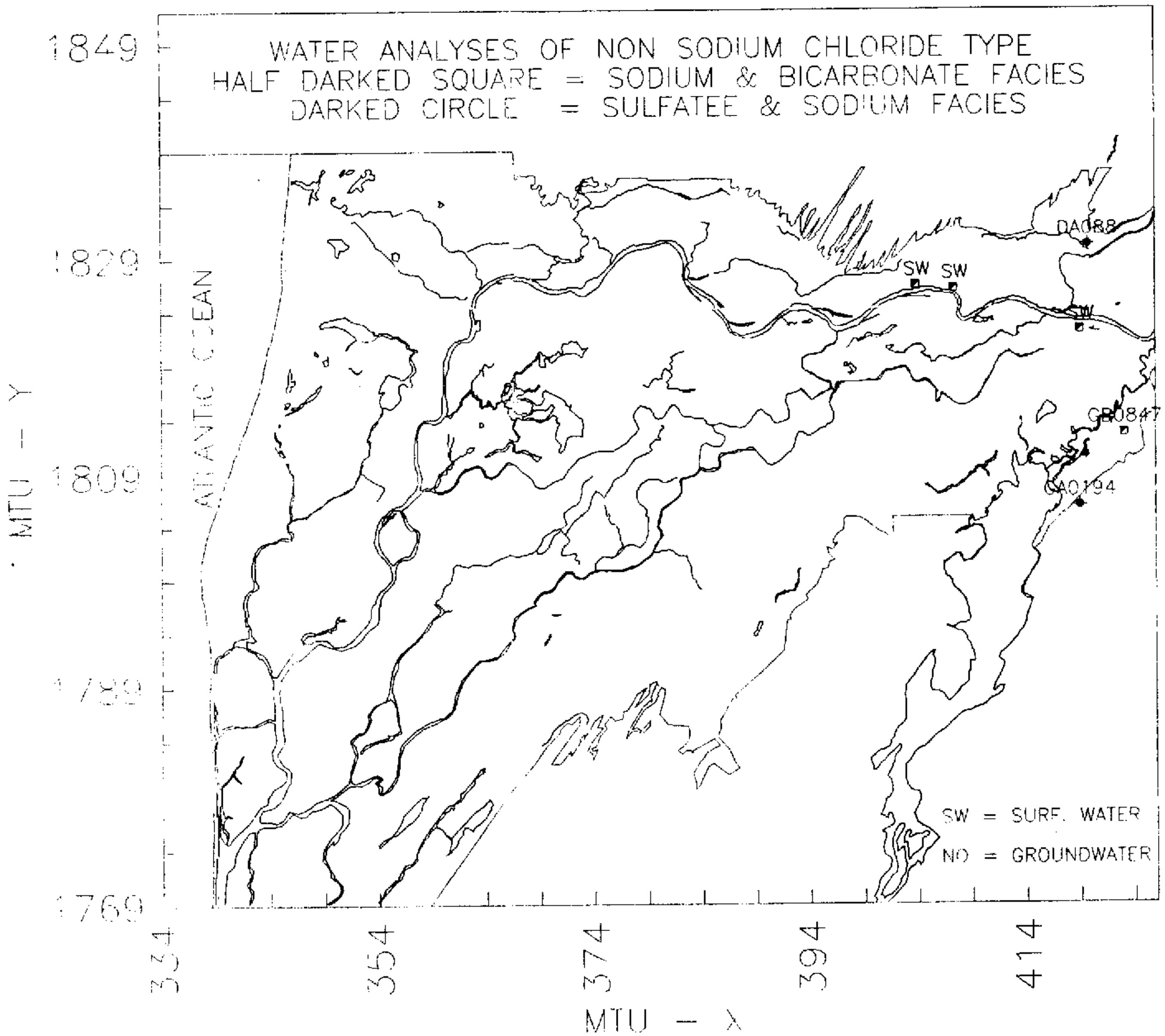
[44] Ref.: COOPERATION ET DEVELOPPEMENT, 1984, p. 95.

[45] Ref.: FREEZE, p. 84.

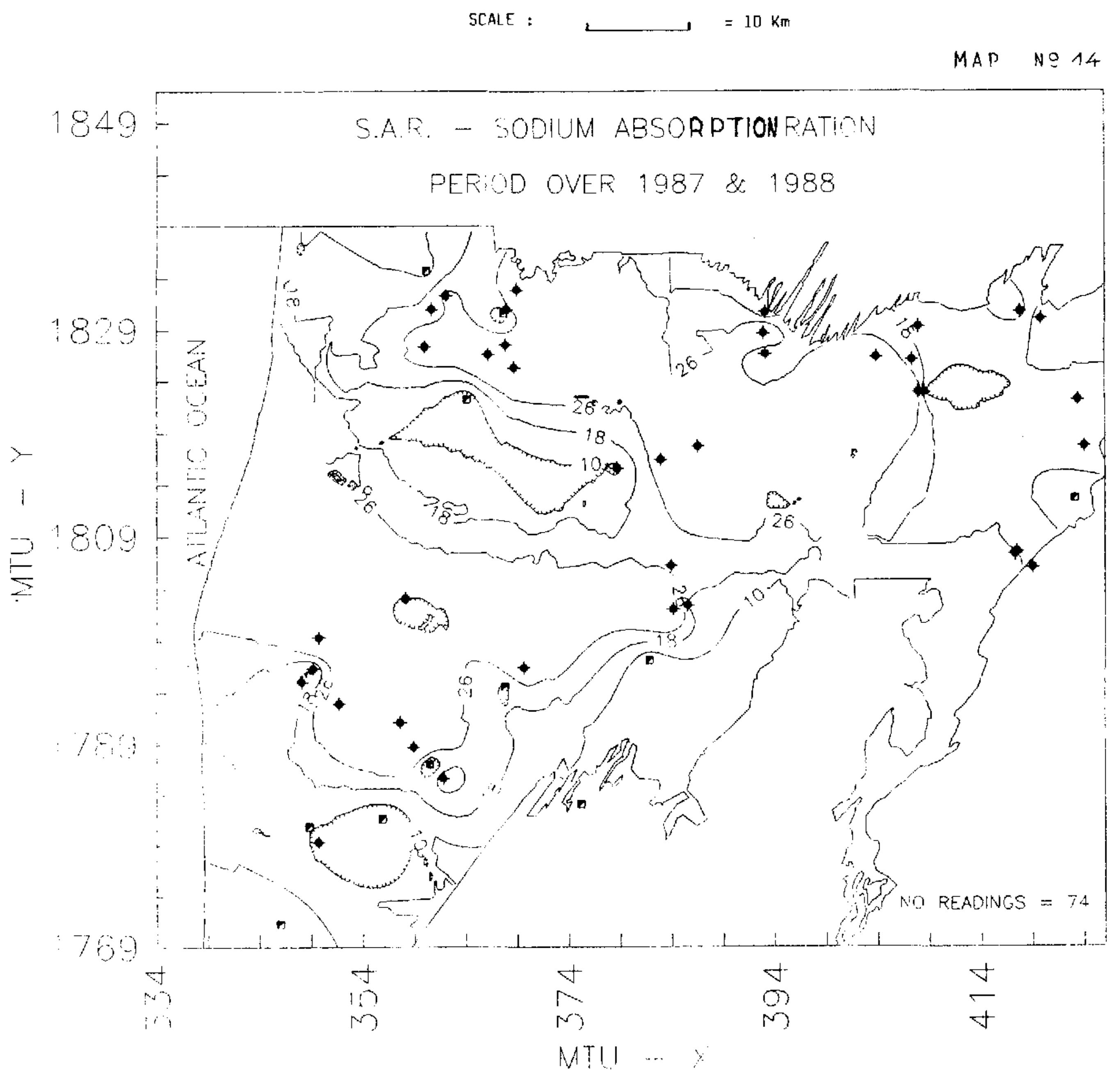
SENEGAL RIVER — DELTA REGION

SCALE : ⊢———⊣ = 10 Km

MAP Nº 13



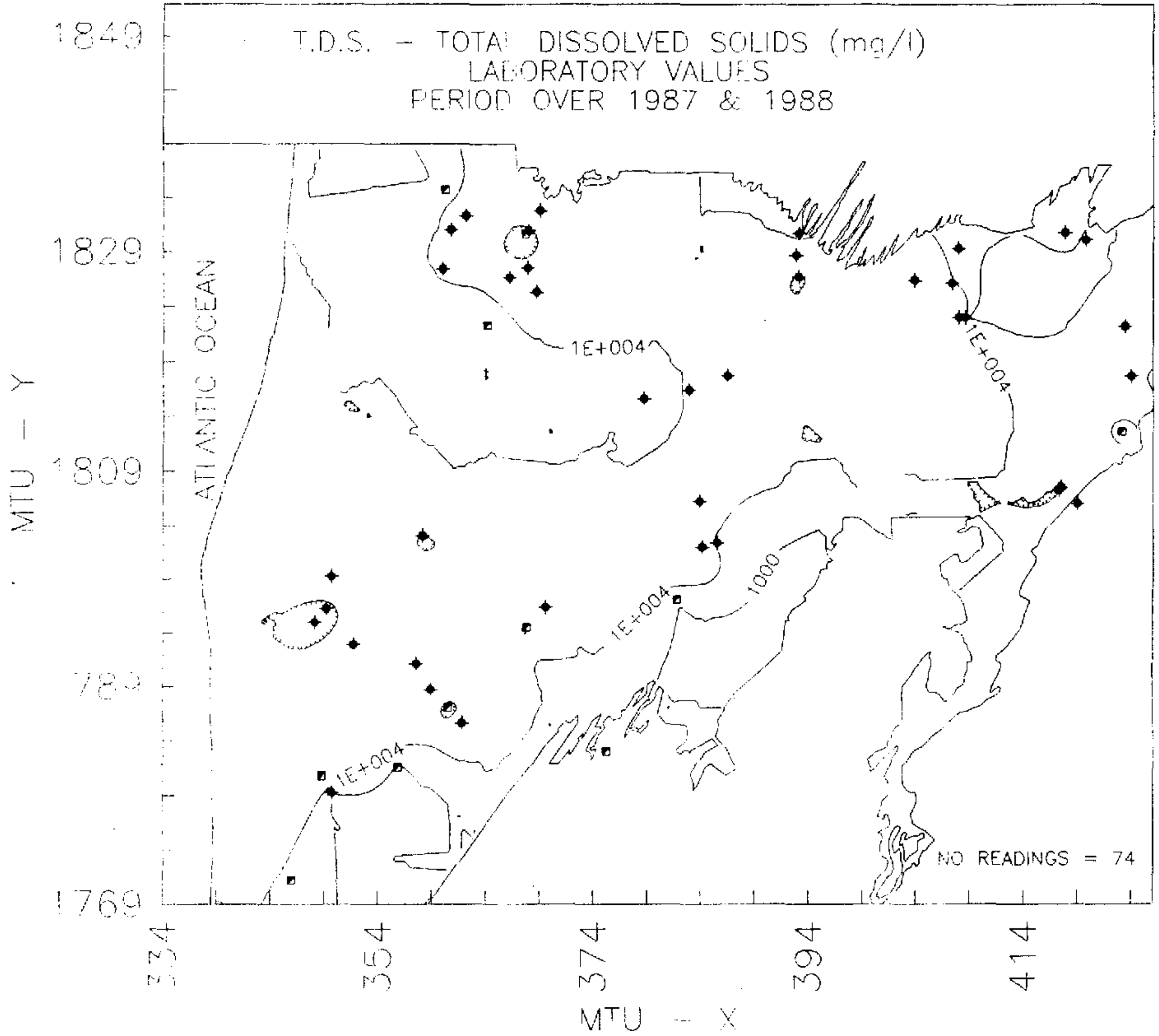
SENEGAL RIVER – DELTA REGION



SENEGAL RIVER – DELTA REGION

SCALE : ______ = 10 Km

MAP Nº 15



* along a N-S axis passing through Lac de Guiers and the town of Rosso, and coincident with the unconfined aquifer zone (see map #25).

The saline water samples come from the zones where the large irrigated perimeters have been developed, except for the CSS and the M'pourie perimeters which are located in the eastern part of the delta in the unconfined aquifer zone. The perimeters are located in heavy soils of the impermeable clay/silt layer #1.

The delta groundwaters are highly mineralized and, considering their high sodium adsorption ratio, are unfit for irrigation.

The surface water samples are practically all (11/15) in the freshwater class. The four T.D.S. surface water values which do not fit this class come from the sloughs (Lampsar, Djeuss and Gorom). This reflects their status of natural drains receiving salt loaded water from fields where the soil is leached before planting.

5.2.4 Pesticides and herbicides

Chemical analyses of the herbicide and pesticide contents of the delta waters are inexistent[46] because local laboratories are not adequately equipped for this kind of specialized analysis.

The project simply inventoried the different pesticides, herbicides and application rates used by organizations like CSS and SAED (see annex #7).

This inventory only concerns the left bank of the delta, even though the same information was requested from SONADER, RIM.

If a sampling campaign is ever made, it should be concentrated near the drainage areas of each of the large irrigated perimeters (see table #2, p.11). These drainage areas constitute high risk zones.

The laboratory analysis of herbicides and pesticides is not currently possible in any of the OMVS member countries.

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[46] Ref.: Gersar, 1989, p. 62.

6 SEASONAL FLUCTUATION CYCLES - PERIOD 1987-1989

The GES data base contains a chronological series of water depth measurements with respect to fixed reference points (groundwater: monthly measurements) and water level data for the bodies of water (surface water: daily measurements).

The hydrogeological monitoring of village wells has been ongoing since November 1986 and that of the piezometers since June 1987, progressively, as they were completed in the field.

The mapping of this data with the Kriging geostatistical treatment permitted the tracing of seasonal depth contours of the water table surface from the ground surface, for the aquifer upper compartment (surface water excluded), and the corresponding potentiometric surfaces (including and excluding surface waters) of the aquifer's upper and lower compartments.

Maps were produced for the ends of the dry and rainy seasons of three hydrogeological cycles (1987-1989). Data stored in GES was extracted for cartographic treatment according to the following criteria:

1) piezometer water intake depth <>13 meters depending on which aquifer compartment was considered,

2) observation periods:
   - 15/05/year < dry season <15/07/year
   - 15/09/year < rainy season <15/11/year

3) cartographic location:
   - 334 < MTU-X < 426
   - 1769 < MTU-Y <1852

The combination of surface water data with groundwater data is based on the sectioning of the delta hydrographic network described in section 3.4 of this report. Characteristic elevations of the surface waters are, for each season and year, described graphically in annex #2. The characteristic elevation for each season is the average value as shown below each graph.

The maps produced with this method are difficult to analyze because the spatial distribution of the OMVS network (see placement criteria, section 3.5 of this report) is very irregular and in the zones where no piezometers exist, the values are extrapolated. As well, the spacing between the piezometers varies with the type of installation:

* metric along the piezometer lines which are transverse to the Senegal River,

* on the scale of kilometers for the piezometers situated inside the large irrigated perimeters and along the piezometer lines which traverse the delta.

The reader should first determine the scale of his analysis.

6.1 Water table depths

Figure #7 indicates the distribution of depths of the water table (m) below the soil surface by increments of 0.5 meters, for the dry and rainy seasons for the period 1987-1989. This log-normal distribution includes depths (m) to the water in wells, in piezometers located within irrigated perimeters (LP) and piezometers located outside of the perimeters (HP).

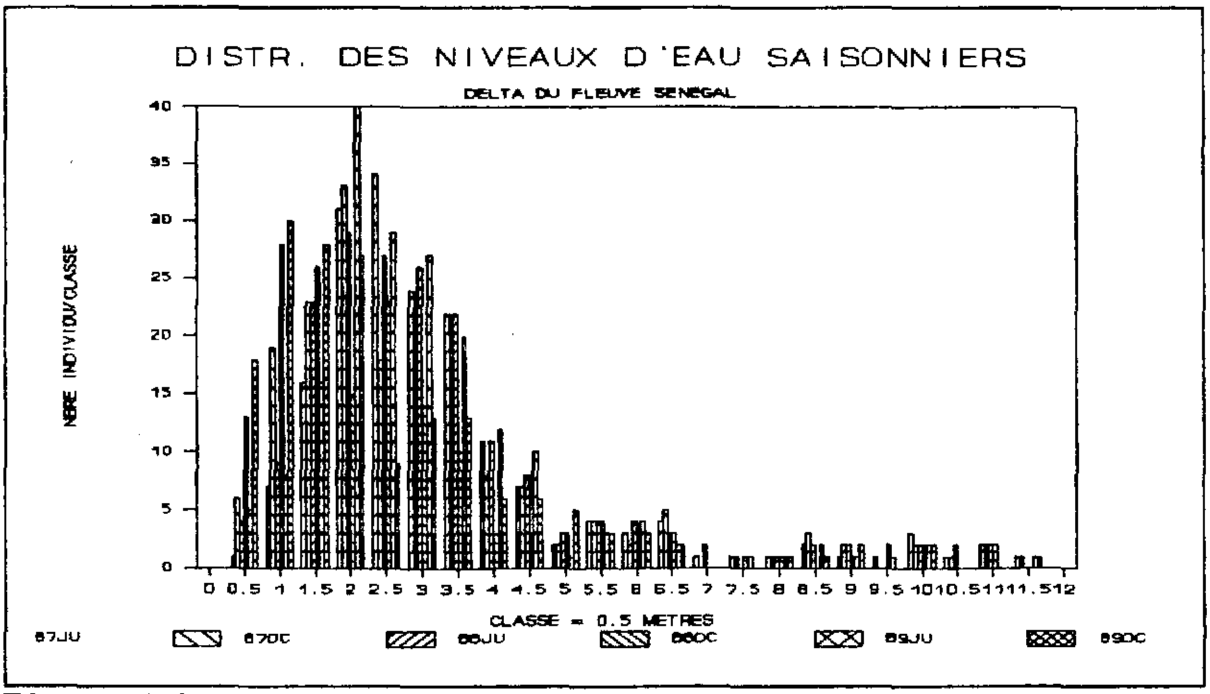


Figure 7 Distribution of water table depths (m) by season

STAT.	JU_87	OC_87	JU_88	OC_88	JU_89	OC_89
NUMBER	180	172	186	157	185	170
MIN	0.14	0.11	0.02	0.02	0.05	0.11
MAX	11.10	11.15	10.99	10.93	11.07	11.11
AVERAGE	3.15	2.82	3.01	2.46	2.79	2.28
STD.DEV.	2.14	2.25	2.11	2.21	1.79	2.03
MEDIAN	2.52	2.06	2.51	2.14	2.41	1.60

The median depth changes seasonally, decreasing during the dry season (evaporation, evapotranspiration) and increasing during the rainy season (infiltration of rainfall and irrigation water).

Compared to the whole period 1987-89, the depth to the water table decreased during 1989.

The map #16 "Water table depth - June 88 (m) - aquifer upper compartment (nv_8806)" and the map #17 "Water table depth - October 88 (m) - aquifer upper compartment (nv_8810)" indicate the seasonal water table depths.

The seasonal fluctuations of the water table (m) can be compared to total annual rainfall measured in the delta (14 raingauges).
Table #5: Period 1986-1989 - annual rainfall

YEAR	1986	1987	1988	1989
NUMBER GAUGES	8	14	9	5
MIN. VAL.	87	68	181	199
MAX. VAL.	402	349	322	388
AVERAGE	214	182	242	268
STD. DEV.	100	81	43	78

GES CODE	RAINGAUGE STATIONS	mm/yr	mm/yr	mm/yr	mm/yr
1	ST LOUIS/AEROPORT	188	349	293	
2	ST LOUIS/ JARDIN BOTAN.		245	268	199
3	NDIOL OUALLO		252		
4	NDIOL DIERI		265	322	388
5	DIAMA BARRAGE		211	181	
6	NDIAYES CENTRE	246	111		215
7	ROSS BETHIO	322	201	224	205
8	BOUNDOUM BARRAGE	187	96		
9	KEUR MACENE	183	68		332
10	ROSSO	402	207		
11	R. TOLL/ KM 8	99	165	215	
12	R. TOLL/ KM 15	87	207	255	
13	R. TOLL/ DOMBO		73	203	
14	R. TOLL/ MBILOR		94	219	

The seasonal maps which follow indicate the depth (m) to the water table for the aquifer' upper compartment only. Surface water data were excluded in producing these maps. There is a slight, seasonal, horizontal displacement of lines of equal water table depth.

The spacing between contour lines of equal water table depth is 1 meter.

The maps indicate drawdown of the water table in the southern part of the delta, (zone of village wells near the Ouallo/Dieri limits), and in the NE part of the delta (zone of wells north of the town of Rosso). Use of the wells influence the drawdowns.

6.2 Potentiometric surfaces (elevations ASL)

The average piezometric values for the different seasons (dry and rainy) over the period of hydrogeological monitoring with the OMVS network, were extracted statistically in consideration of the geographic location of the piezometers:

* inside the limits of the large irrigated perimeters (piezometer numbering code LP),

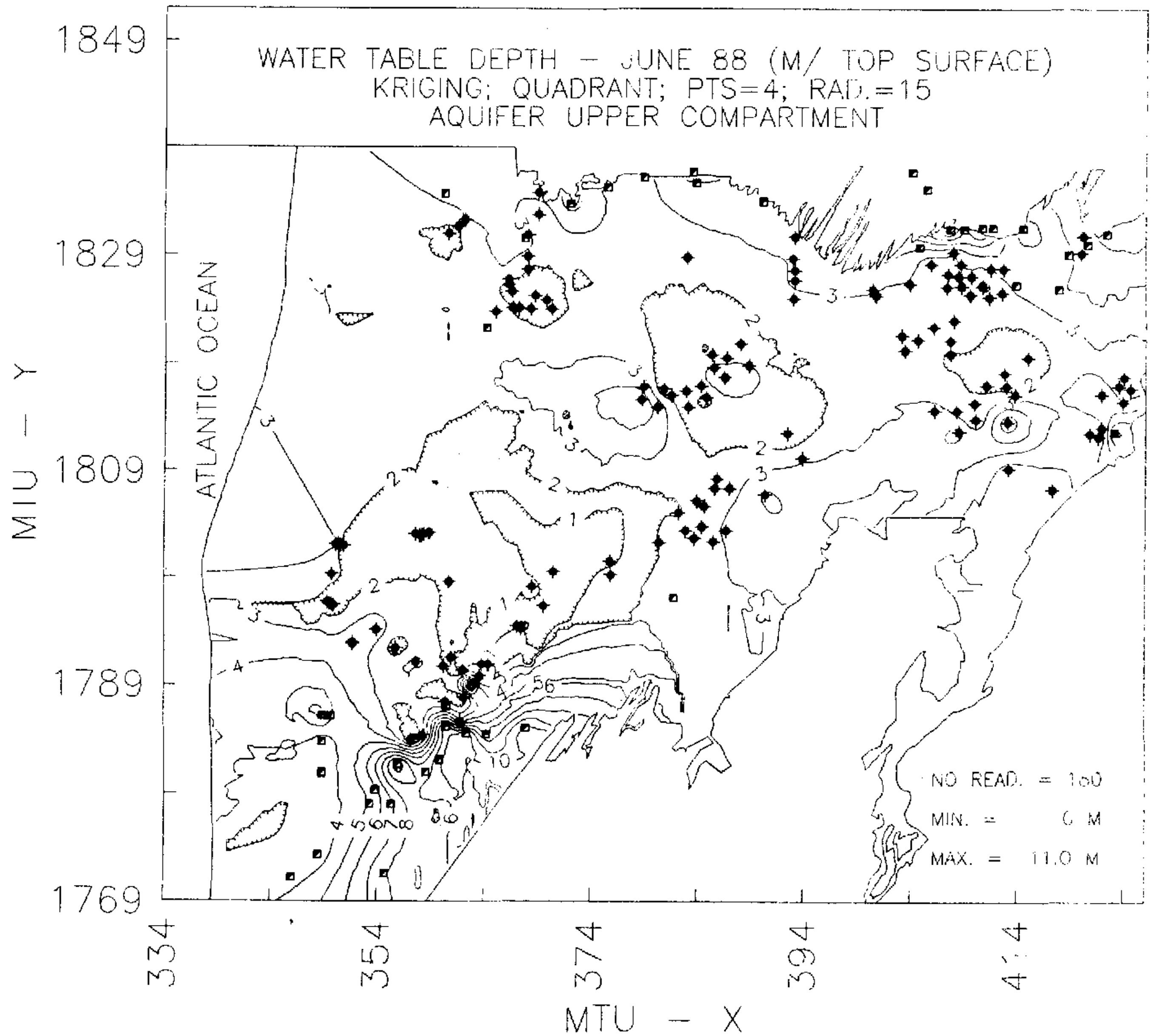
PIEZOMETRY STATISTICS	1987 DRY	1987 RAINY	1988 DRY	1988 RAINY	1989 DRY	1989 RAINY
NUMBER DATA	72	115	118	108	125	120
MIN.	-3.27	-2.36	-2.40	-2.33	-2.47	-2.37
MAX.	2.25	2.30	1.89	2.68	1.76	2.63
AVERAGE	-0.45	0.03	-0.29	0.26	-0.33	0.43
STD. DEV.	0.93	1.02	0.85	0.96	0.86	0.99

* outside the limits of the large irrigated perimeters (piezometer numbering code HP),

SENEGAL RIVER – DELTA REGION

SCALE : ⊢——⊣ = 10 Km

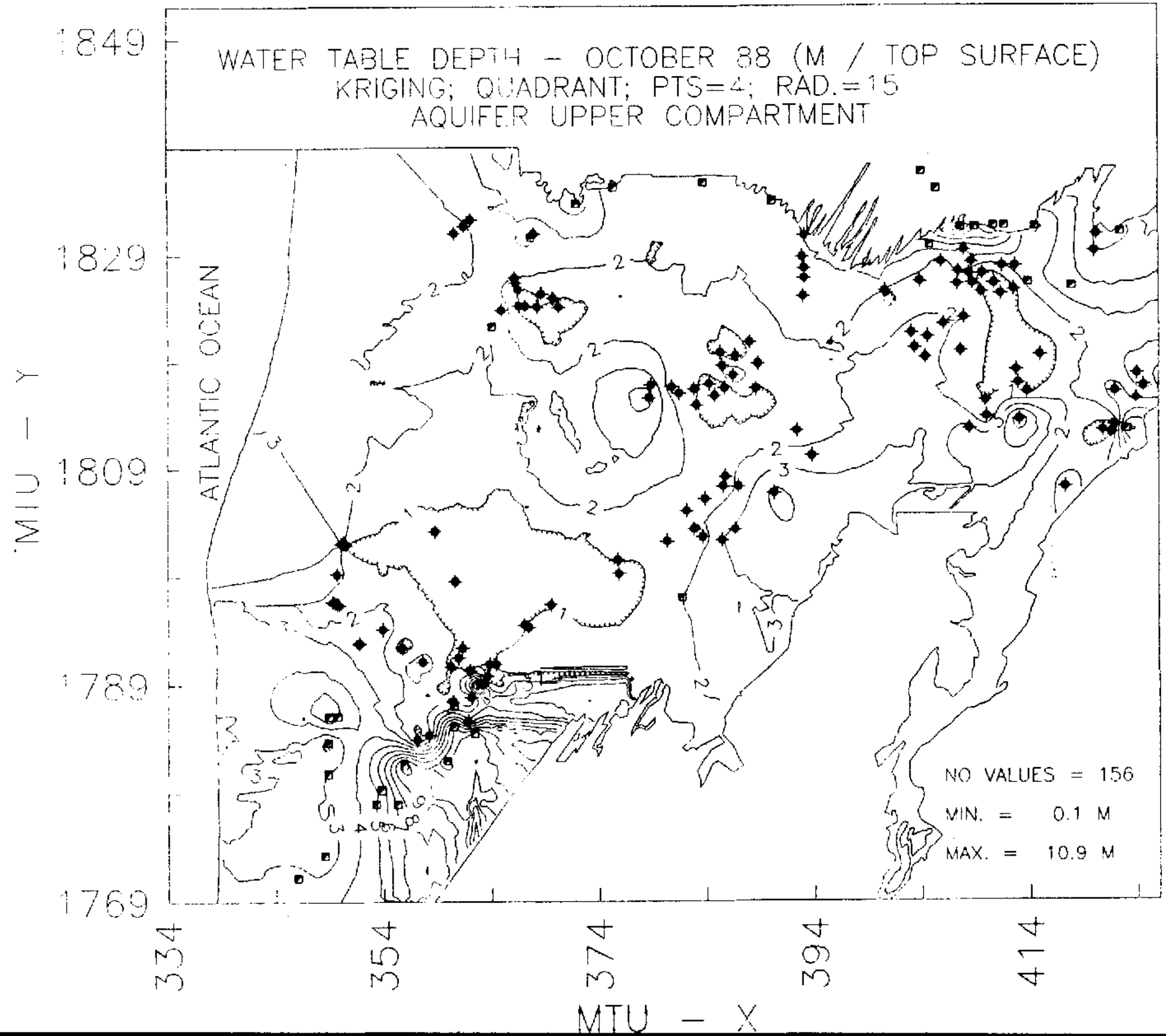
MAP Nº 16



SENEGAL RIVER - DELTA REGION

SCALE : ▁▁▁▁ = 10 Km

MAP Nº 17



PIEZOMETRY STATISTICS	1987 DRY	1987 RAINY	1988 DRY	1988 RAINY	1989 DRY	1989 RAINY
NUMBER DATA	22	38	56	45	57	46
MIN.	-4.55	-4.10	-3.28	-3.00	-4.39	-4.33
MAX.	0.30	1.07	1.86	1.14	1.76	0.86
AVERAGE	-0.56	-0.57	-0.53	-0.23	-0.71	-0.44
STD. DEV.	1.14	1.21	0.96	1.10	0.98	1.15

The piezometric contours based on observation points outside the limits of the large irrigated perimeters are, on the average, systematically negative, regardless of the season. The positive values are for piezometers located near watercourses.

The piezometric contours based on observation points inside the irrigated perimeters are, on the average, negative during the dry season and positive during the rainy season. The rainy season also corresponds to the "hivernage" agricultural season (infiltration of irrigation water).

The average seasonal fluctuations of the water table are shown in the following table.

Table #6: Average seasonal fluctuations of the water table

YEAR	1987	1988	1989
IN PERIMETERS	0.48	0.55	0.76
OUTSIDE PERIMETERS	-0.01	0.30	0.27

These average seasonal fluctuations of the water table do not reflect the heterogeneity of the aquifer. The following table lists the variations in piezometric head (confined aquifers) and water table level (unconfined aquifers) for several regions of the delta. The variations are related to shape and structural characteristics of the aquifer.

Table #7: Regional observations concerning seasonal variations in piezometric head and water table elevation

REGION	ST.	LAYER #1		-------AQUIFER--------			IRR.	SEAS.VAR'N.			I vert.+/-			AQUIFER TYPE		
		THICK (m)	DISC.	ROOF m ASL	WALL m ASL	THICK (m)	Y/N	87 (m)	88 (m)	89 (m)	87	88	89	87 U/C	88 U/C	89 U/C
TOUNDOU BIRETTE	W	0	N/A	+6	-8	14	N	0.2	0.6	0.3	N/A	N/A	N/A	U	U	U
AXE LAMPSAR + CUVETTES GDTK	LP	2, 4	NO	-2, -3	-8	8, 10	Y	0.2	0.6	0.5	+	+	+	C	C	C
NORD CUVETTE NGAEL	HP	0, 1	YES	0, -1	-10	8	N	0.1	0.1	0.1	-	-	-	U	U	U
BOUNDOUM	LP	2	YES	0, -2	-10	8	?	0.3	0.3	0.4	-	-	-	U+C	U+C	U+C
DEBI	LP	0, 6	YES	0, -6	-8	0, 2	?	0.2	0.6	0.4	-	-	-	C	C	C
CSS, BALKY,SOUSSE	LP	0, 2	YES	0, -2	-12	8, 10	Y	1.0	1.0	1.0	+	+	+	U+C	U+C	U+C
TAHOUEY, DOMBO	LP	2, 4	YES	-2, -3	-12	10	?	0.9	0.9	1.3	+	+	+	C	C	C
THIAGAR	LP	2, 4	YES	0, -2	-8	8	?	1.3	0.2	1.6	+	+	+	U+C	U+C	U+C
MPOURIE	LP	4	YES	-4	-8, -12	8	Y	1.4 0.5	1.4 0.6	1.4 0.6	+	+	+	U C	U C	U C
KEUR MACENE	LP	4	NO	-4	-12	8	N	0.0	0.2	0.2	+	+	+	C	C	C
LB- LIMITS OUALLO/DIERI	W	0	N/A	+5	-8	8, 10	N	0.0	0.1	0.1	N/A	N/A	N/A	U	U	U
RB- LIMITS OUALLO/DIERI ROSSO	W	0	N/A	+3	-14, -16	16	N	0.0	0.2	0.2	N/A	N/A	N/A	U	U	U
RB- LIMITS OUALLO/DIERI KEUR MACENE	W	0	N/A	+2	-8	10	N	0.5	0.6	0.0	N/A	N/A	N/A	U	U	U

Legend for table #7:

ST. = HP = outside perimeter; LP = within perimeter limits; W = village,
DISC. = discontinuity in clay/silt layer #1
ROOF = aquifer upper surface elevation
WALL = lateral aquifer limits of the upper compartment
U/C = U = unconfined; C = confined
IRR. = irrigation in the region concerned Y=yes; N=no
I vert.= vertical hydraulic gradient between the upper and lower compartments (+)=downward; (-)=upward.

From the table, we note that:

1) in the unconfined aquifer zones:

* in the center of the delta, outside irrigated perimeters (Ngael Nord depression), the seasonal water table fluctuations are insignificant, on the order of 0.1 meter,

* on the Ouallo/Dieri limits, outside irrigated perimeters, the seasonal water table fluctuations are insignificant,on the order of 0.1 to 0.2 meter,

* within the limits of the irrigated perimeters, the seasonal water table variations are from 0.9 to 1.6 meters,

* in the toundous, zones of discontinuity of impermeable layer #1, the seasonal water table fluctuations are on the order of 0.3 meter.

2) in the confined aquifer zones:

* within the limits of the irrigated perimeters, the seasonal fluctuations are on the order of 0.3 to 0.4 meter.

The reader will find on the following pages:

* map #18 "Potentiometric surface - June 88 - with surface waters - aquifer upper compartment (m ASL) (z1_8806)",

* map #19 "Potentiometric surface - June 88 - without surface waters - aquifer upper compartment (m ASL) (zgw8806)",

* map #20 "Potentiometric surface - October 88 - with surface waters - aquifer upper compartment (m ASL) (z1_8810)",

* map #21 "Potentiometric surface - October 88 - without surface waters - aquifer upper compartment (m ASL) (zgw8810)",

* map #22 "Water table variations (meters) between June and October 88 - with surface waters (re_88106)"

* map #23 "Water table variations (meters) between June and October 88 - without surface waters (zgw_1006)"

These maps show the potentiometric surface variations and the water table fluctuations for the months of June and October 88, including and excluding surface water level elevation data during the geostatistical calculations.

6.3 Confined and unconfined aquifer zones

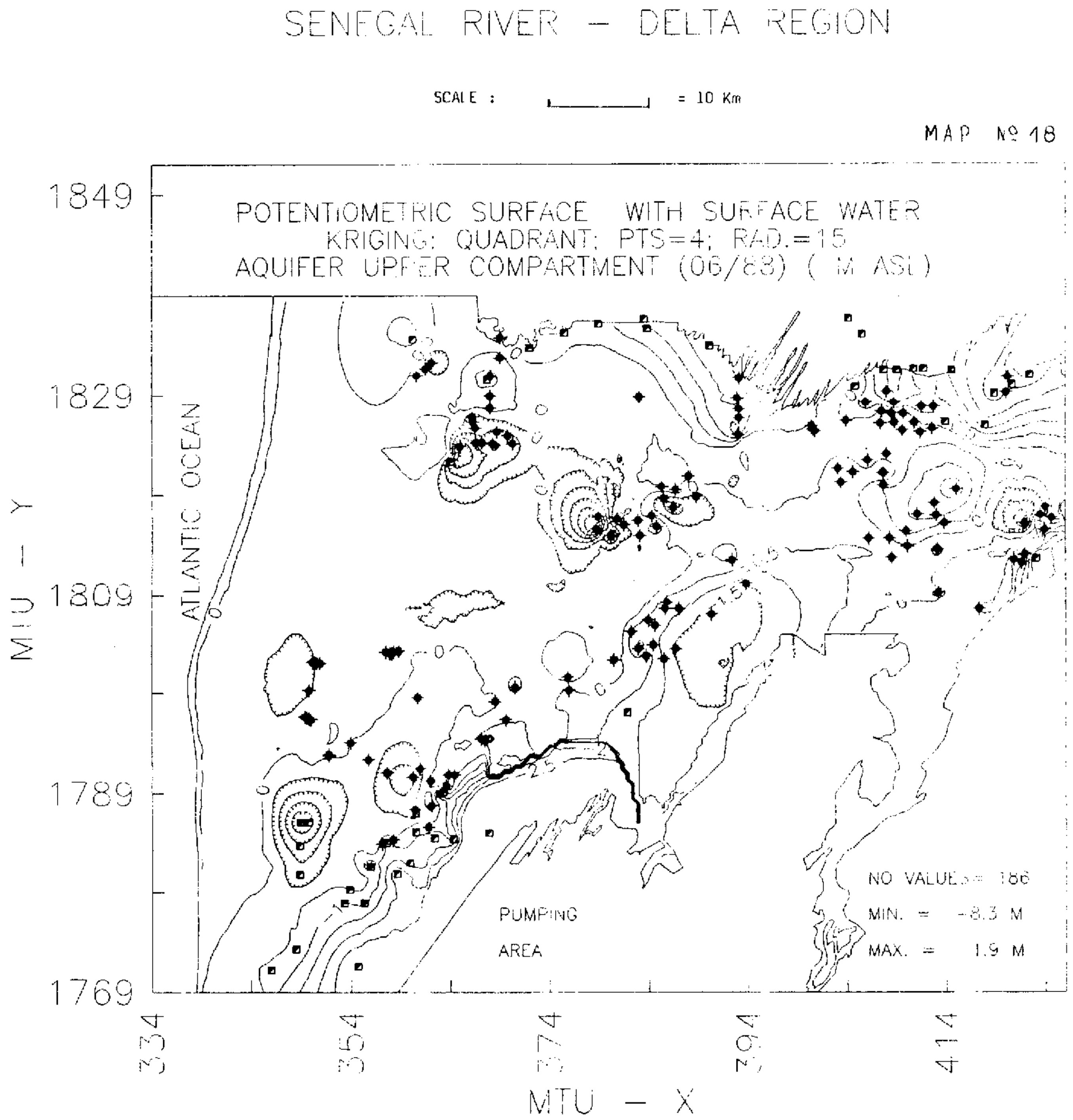
Subtraction of the seasonal potentiometric surfaces from the upper surface of the aquifer's upper compartment was performed in order to develop map #24 "Confined and unconfined aquifer zones - June 88 (ty_8806)" and map #25 "Confined and unconfined aquifer zones - October 88 (ty_8810)". The zero contour line delimits the two: confined aquifer = negative values; unconfined aquifer = positive value. Hashing was added to make the unconfined aquifer zones more visible.

This information is significant near the piezometers but not elsewhere.

The unconfined aquifer zones coincide perfectly with the map indicating discontinuities in the #1 clay/silt layer (see section 4.2.1) and the comments made in that chapter apply equally well to the unconfined aquifer zones.

The confined aquifer zone covers most of the central part of the delta and coincide well with the zones of highest T.D.S. (total dissolved solids). These waters are trapped under an effectively impermeable clay layer.

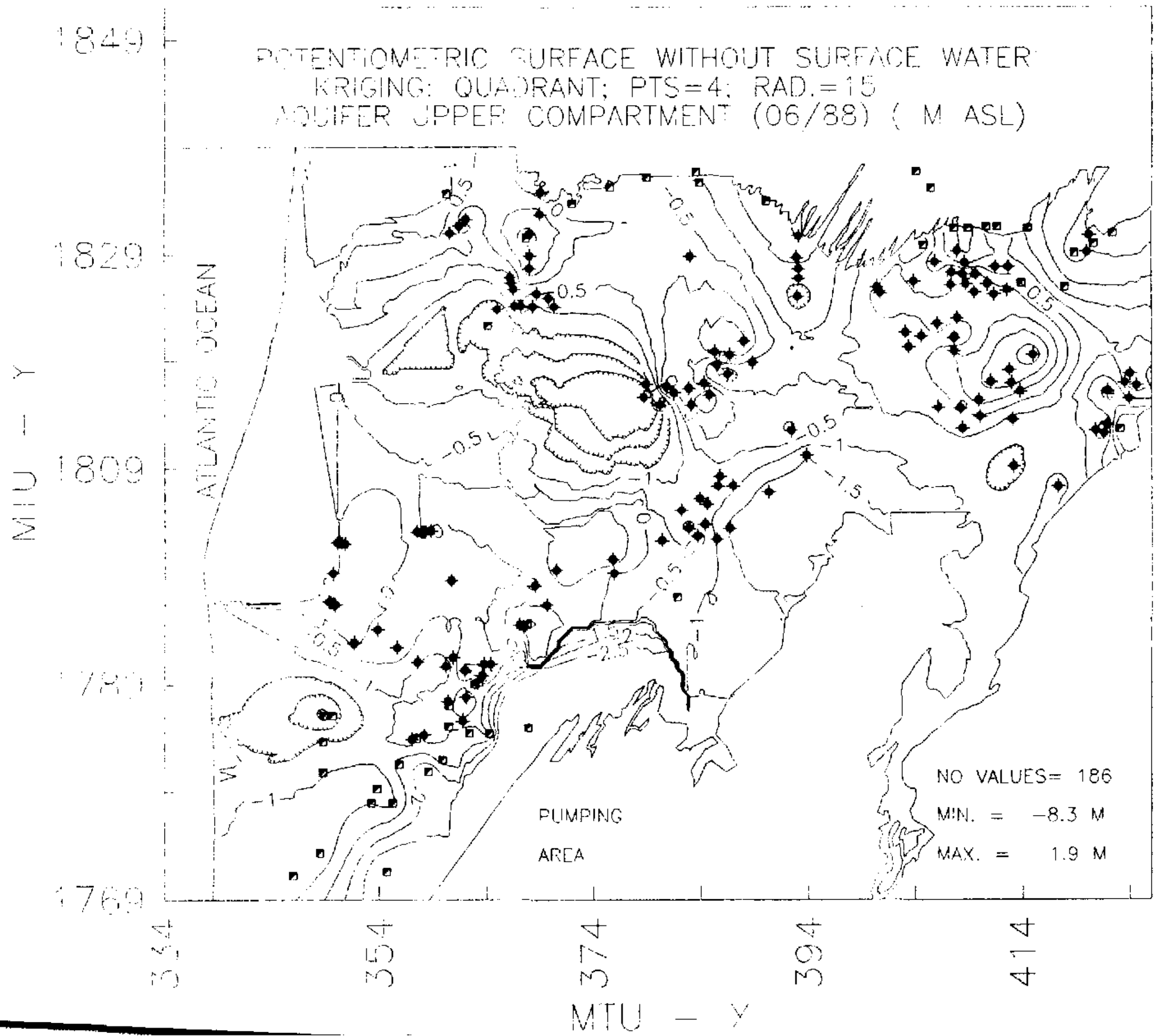
The surface areas of the confined and unconfined aquifer zones vary with the season as indicated below:


SENEGAL RIVER - DELTA REGION
SCALE : = 10 Km
MAP Nº 18
POTENTIOMETRIC SURFACE WITH SURFACE WATER
KRIGING: QUADRANT; PTS=4; RAD.=15
AQUIFER UPPER COMPARTMENT (06/88) (M ASL)
ATLANTIC OCEAN
PUMPING
AREA
NO VALUES = 186
MIN. = -8.3 M
MAX. = 1.9 M
1849
1829
1809
1789
1769
334
354
374
394
414
MTU - Y
MTU - X

SENEGAL RIVER – DELTA REGION

SCALE : ———— = 10 Km

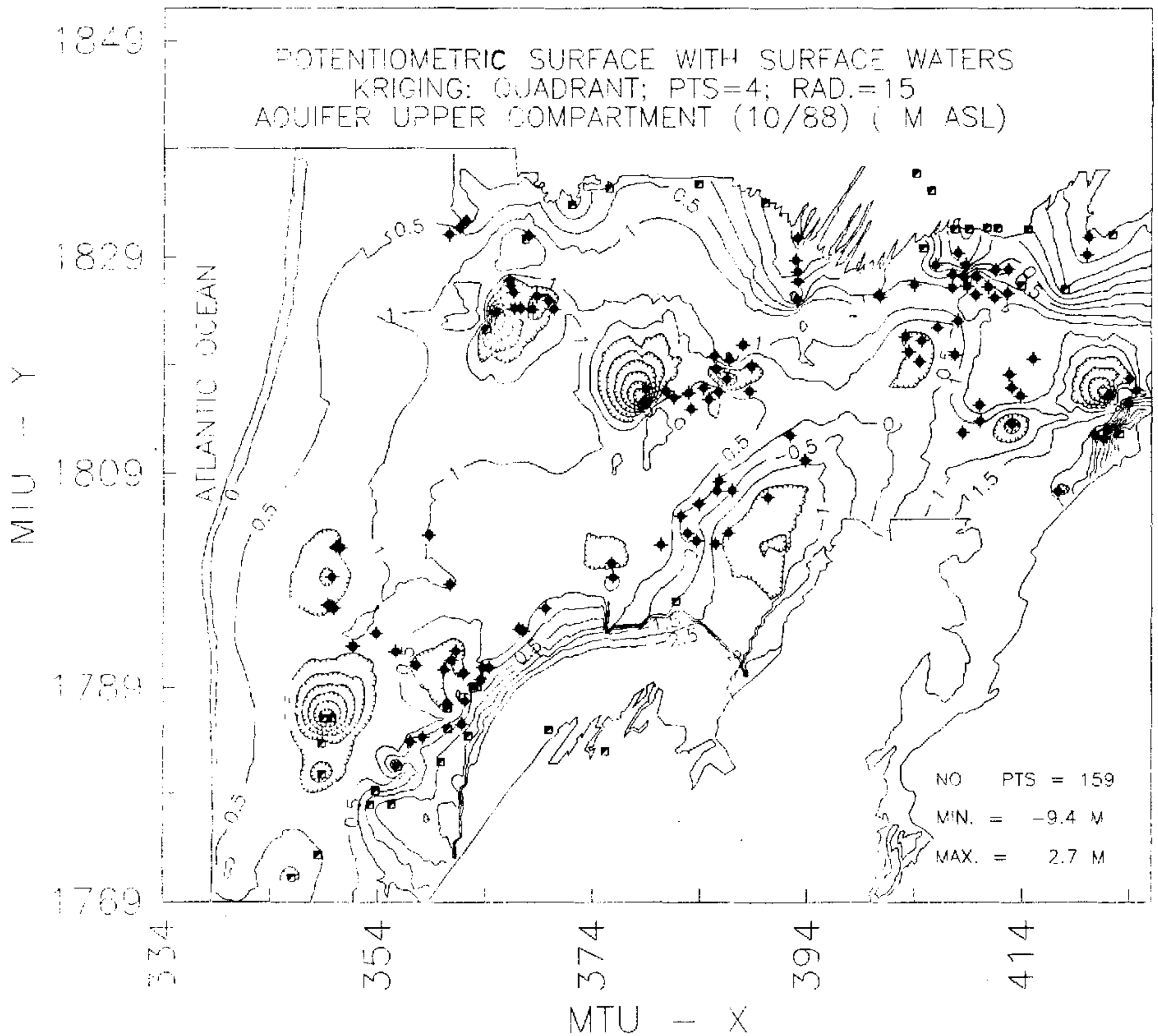
MAP Nº 19



SENEGAL RIVER – DELTA REGION

SCALE : ⊢——⊣ = 10 Km

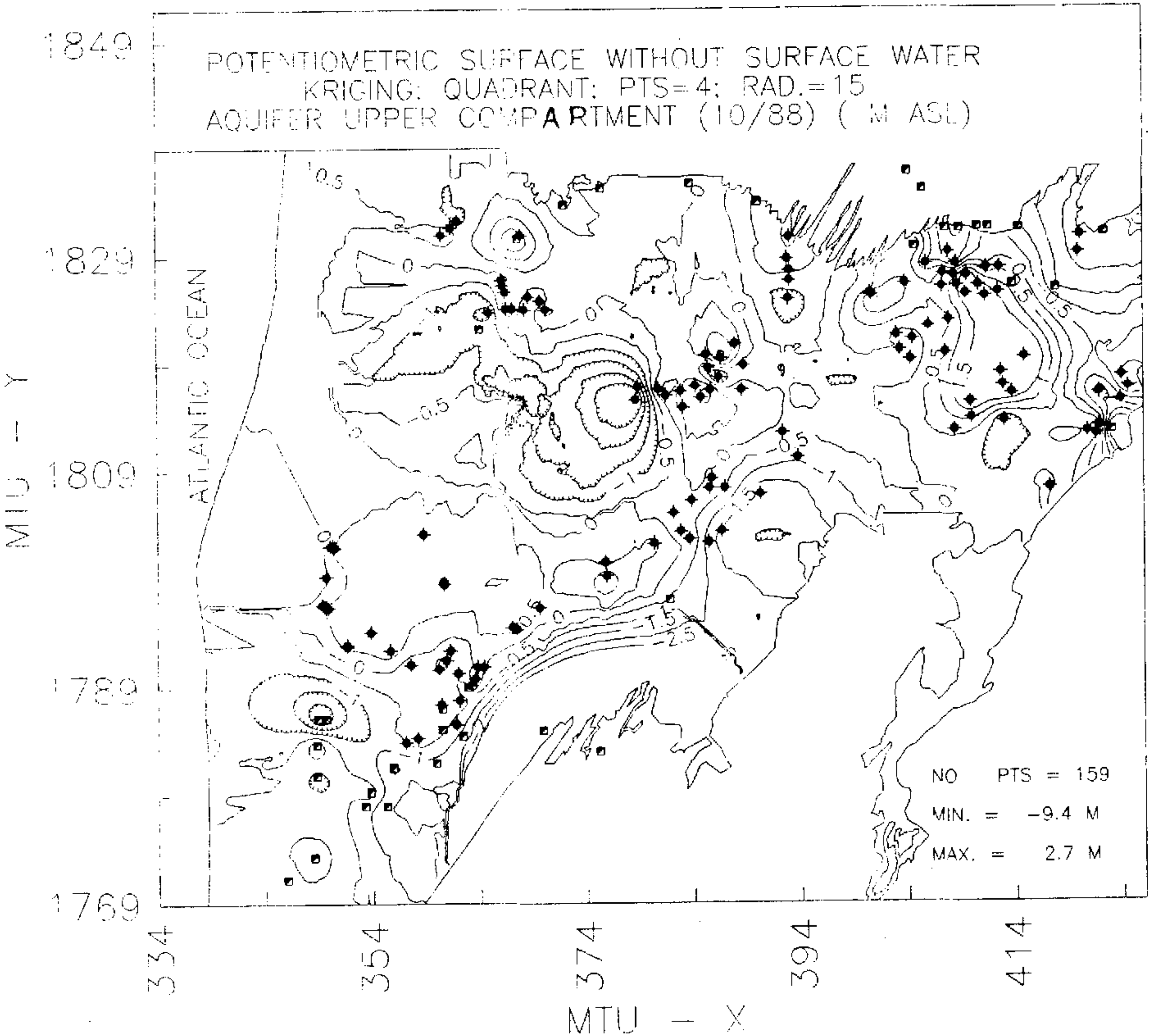
MAP Nº 20



SENEGAL RIVER – DELTA REGION

SCALE : = 10 Km

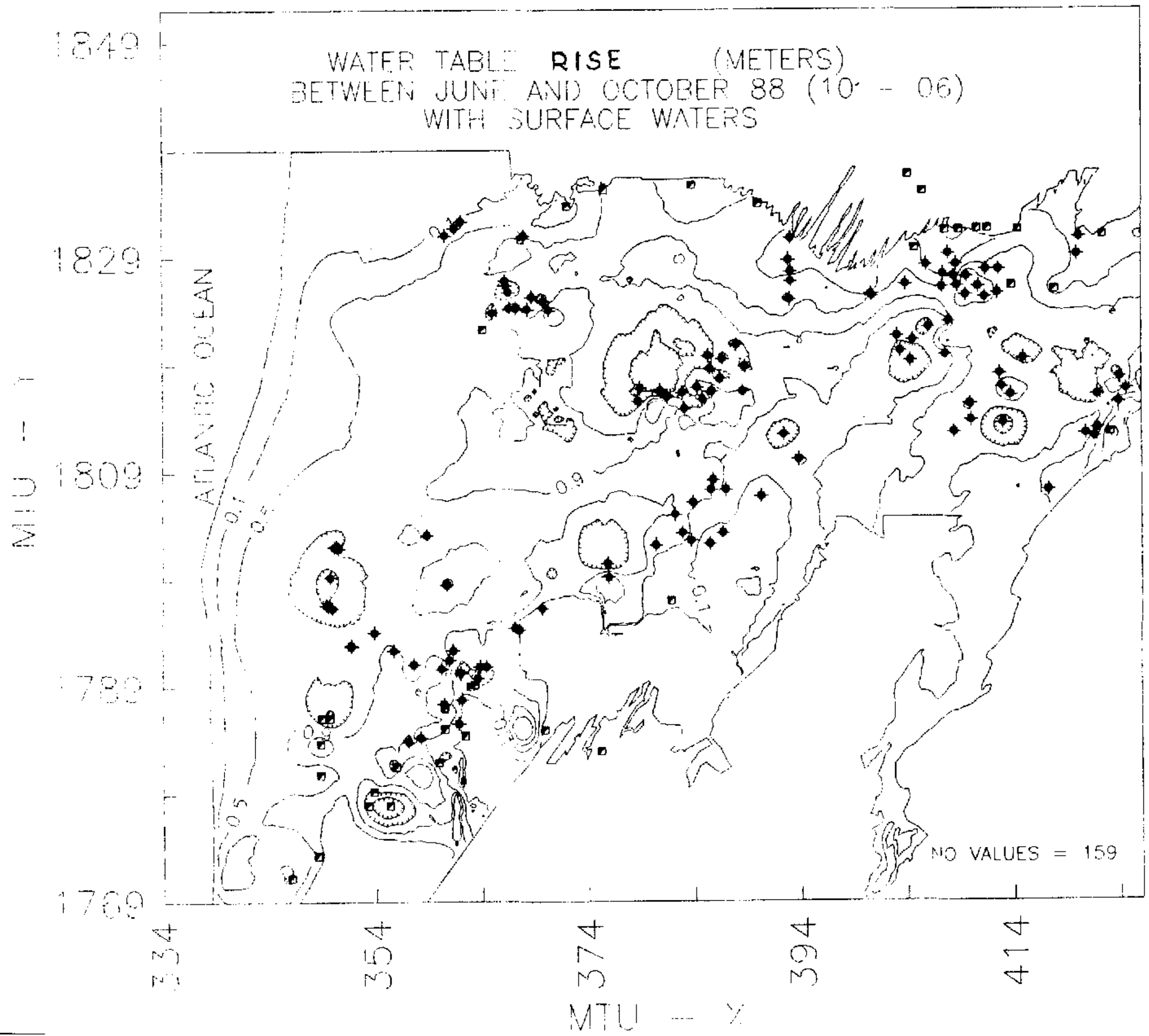
MAP Nº 21



SENEGAL RIVER – DELTA REGION

SCALE : ⊢——⊣ = 10 Km

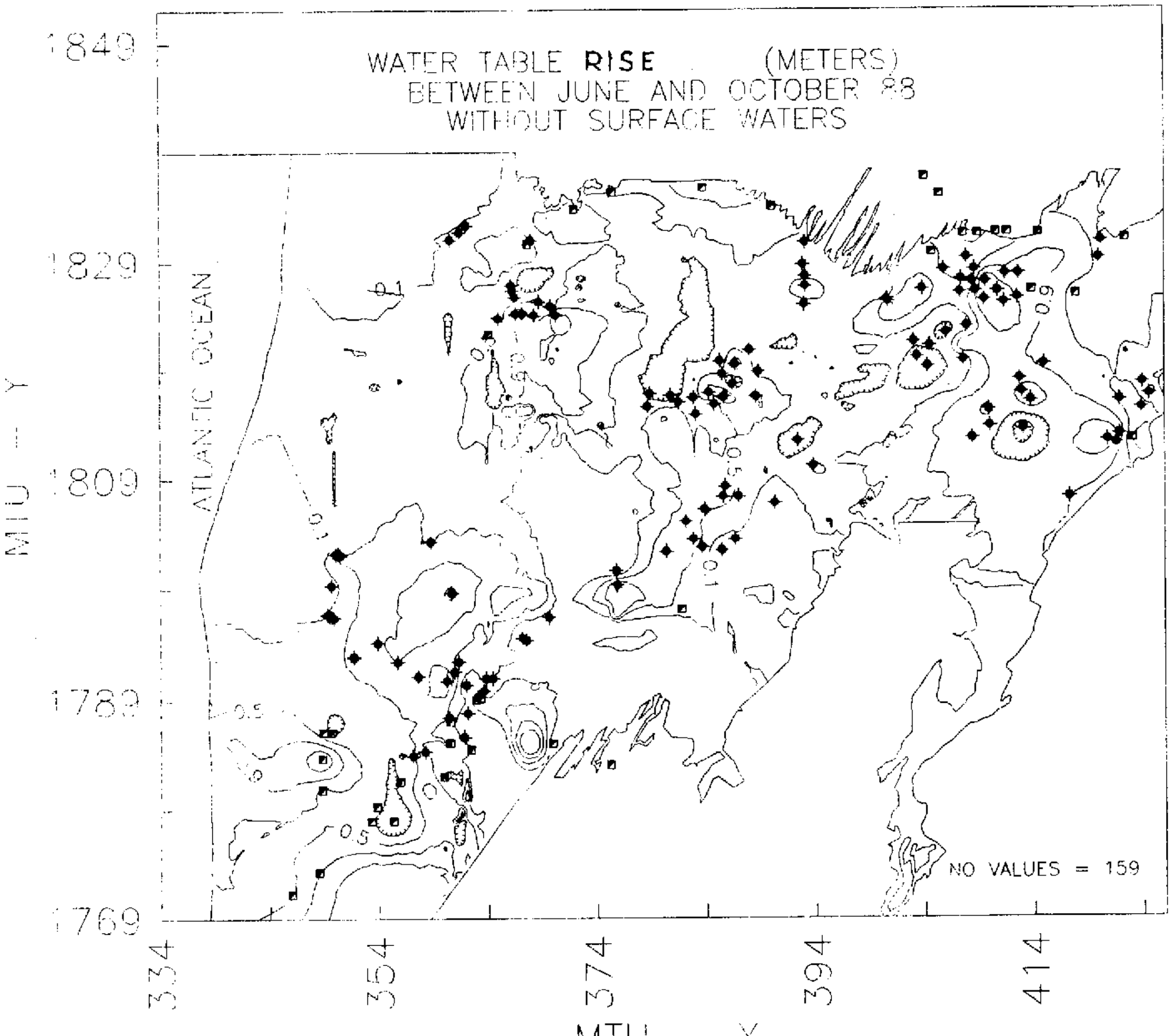
MAP Nº 22



SENEGAL RIVER – DELTA REGION

SCALE : ⊢———⊣ = 10 Km

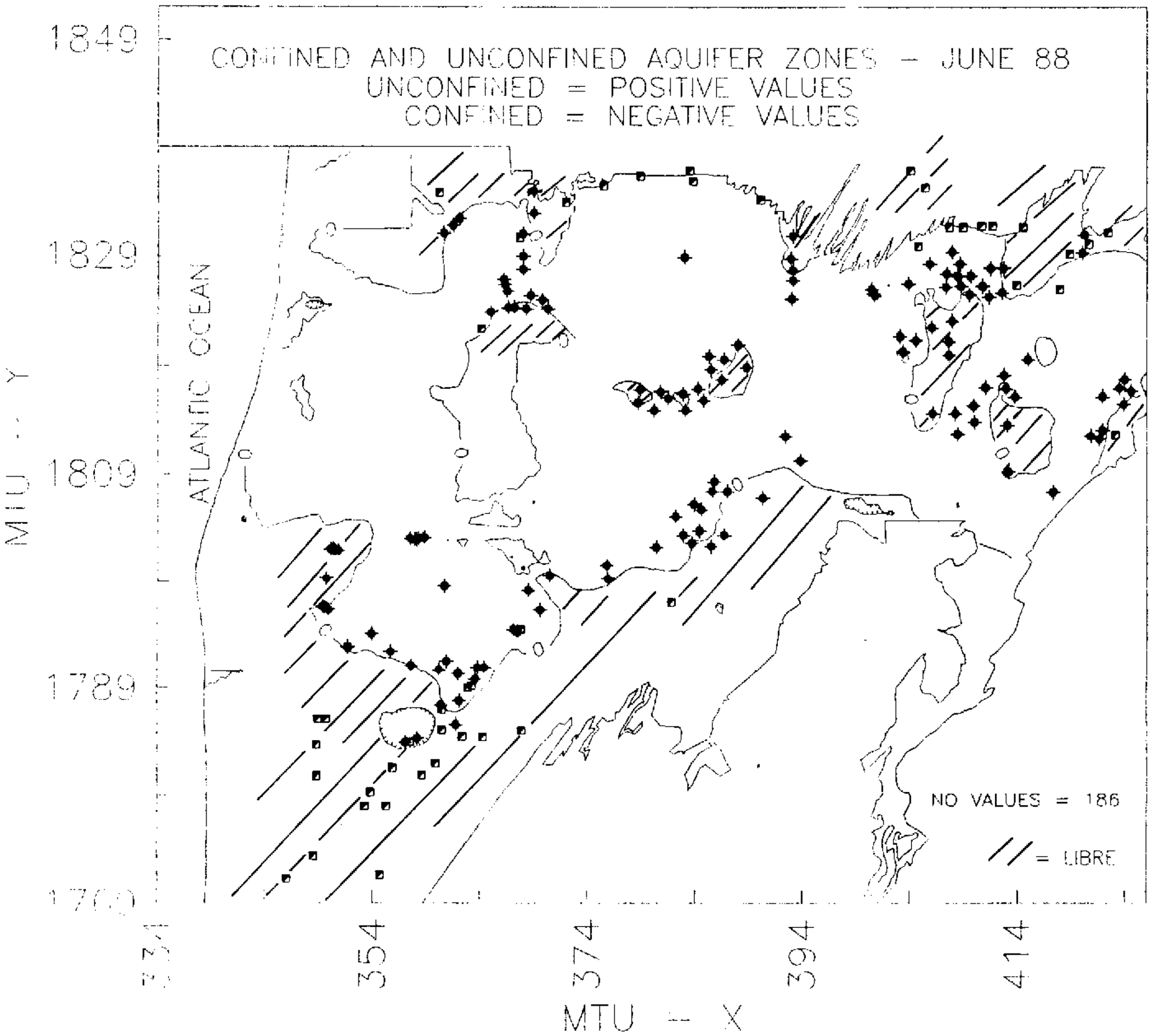
MAP Nº 23



SENEGAL RIVER – DELTA REGION

SCALE : ⎵⎵⎵⎵ = 10 Km

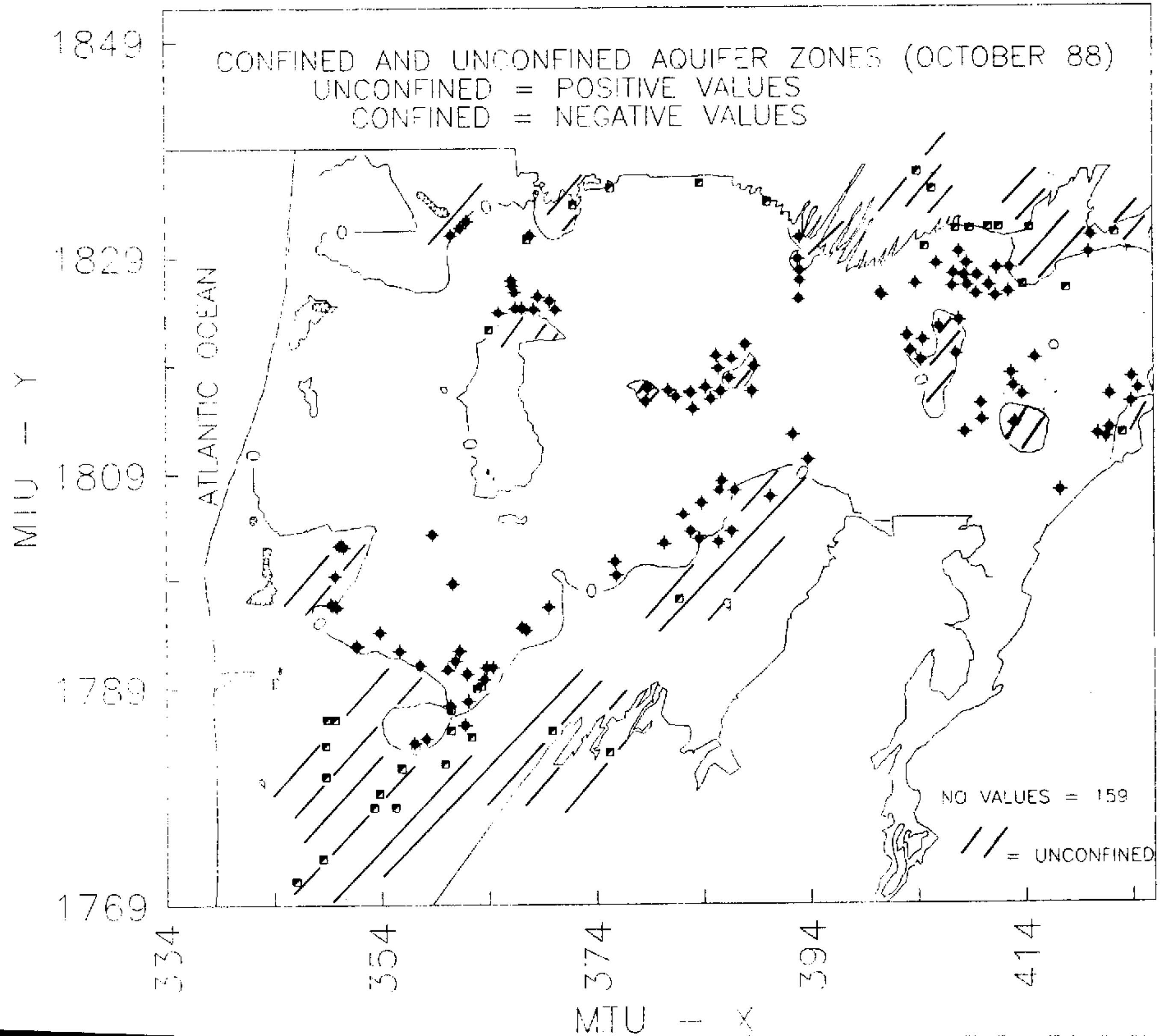
MAP Nº 24



SENEGAL RIVER - DELTA REGION

SCALE : ⊢——⊣ = 10 Km

MAP Nº 25



PERIOD	CONFINED AQUIFER km2	FRACTION OF DELTA %	UNCONF. AQUIFER km2	FRACTION OF DELTA %	DELTA TOTAL km2
JUNE_87	2353	54.2%	1991	45.8%	4344
OCT_87	2563	59.0%	1781	41.0%	4344
JUNE_88	2403	55.3%	1941	44.7%	4344
OCT_88	2577	59.3%	1767	40.7%	4344
JUNE_89	2386	54.9%	1958	45.1%	4344
OCT_89	2631	60.6%	1713	39.4%	4344

The seasonal variations in surface area of the confined and unconfined aquifers are minor except for near Thiagar perimeter, south of the town of Rosso. The surface area variations are proportional to the (minor) seasonal variations in piezometric head (see section 6.1). Because of the absence of the semi-permeable layer, the unconfined aquifer zones are favorable locations for recharge.

6.4 Electrical conductivity values (µS/cm = micro Siemens per cm)

The electrical conductivity of the groundwater in wells and piezometers was measured monthly during the period 1987-1989. Table #8 indicates the distribution of conductivity values by class of 5000 µS/cm, at the end of the dry season (June/year) and the rainy season (October/year). These distributions are indicative of the aquifer upper compartment only.

Table #8: Distribution of seasonal electrical conductivity values

CLASSES	JUNE_87	OCT_87	JUNE_88	OCT_88	JUNE_89	OCT_89
0 to 5000	90.00%	90.91%	67.74%	53.42%	53.51%	51.48%
5000 to 10000	8.00%	6.82%	19.35%	9.32%	14.05%	8.88%
10000 to 15000	2.00%	2.27%	8.06%	10.56%	11.35%	10.65%
15000 to 20000	0.00%	0.00%	2.69%	4.97%	8.11%	5.92%
20000 to 25000	0.00%	0.00%	1.08%	3.73%	0.54%	0.59%
25000 to 30000	0.00%	0.00%	0.54%	6.21%	0.54%	1.18%
30000 to 35000	0.00%	0.00%	0.54%	3.11%	0.00%	0.59%
35000 to 40000	0.00%	0.00%	0.00%	3.73%	1.62%	3.55%
40000 to 45000	0.00%	0.00%	0.00%	1.24%	2.70%	5.92%
45000 to 50000	0.00%	0.00%	0.00%	3.73%	2.70%	0.59%
50000 to 55000	0.00%	0.00%	0.00%	0.00%	1.08%	1.78%
55000 to 60000	0.00%	0.00%	0.00%	0.00%	0.54%	3.55%
60000 to 65000	0.00%	0.00%	0.00%	0.00%	1.62%	0.59%
65000 to 70000	0.00%	0.00%	0.00%	0.00%	0.54%	0.00%
70000 to 75000	0.00%	0.00%	0.00%	0.00%	0.00%	0.59%
75000 to 80000	0.00%	0.00%	0.00%	0.00%	0.54%	2.37%
80000 to 85000	0.00%	0.00%	0.00%	0.00%	0.54%	1.78%
85000 to 90000	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
90000 to 95000	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
95000 to100000	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
BEYOND	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
NUMBER	50	44	186	161	185	169
MIN	175	390	110	110	90	68
MAX	10500	13500	33000	50000	82800	84960
AVERAGE	1910	2684	4997	11391	11121	15530
STD. DEV.	2107	2463	5354	13542	16484	21947
MEDIAN	1000	1950	2900	5000	3000	4750

The number of measurements made in 1987 is less than one third of the number made in the following years. The conductivity values for 1987 were all for samples drawn from village wells, none from piezometers. For this reason, the 1987 measurements will not be considered in the following discussion since they are not considered representative of the conditions in the rest of the delta (marginal geographic location on the Ouallo/Dieri limits). From table #8, we notice an increase in conductivity with time. No reasonable geological or hydrogeological explanation can explain this increase in the electrical conductivity as a function of time. It would seem, therefore, that the field procedures and instruments used are at the cause.

Two conductivity meters, of different types, were used:

* Yellow Spring Instruments, model 33, scale range from 0 to 50,000 µS/cm, used from November 1986 until mid April 1989,

* Schott Gerate, model CG857, scale range from 0 to 20,000 µS/cm, used since April 1989.

The range of electrical conductivities in the delta is large. Values are sometimes greater than 70,000 µS/cm, necessitating the dilution of samples before measurement (probable source of error).

The depth at which the measurements are made is also important, as shown by the measurements made by ORSTOM inside of several OMVS network piezometers (shallow and deep). Figure 8 (deep piezometer GA0201) and figure 9 (shallow piezometer GA0147) illustrate the increase in conductivity with increasing depth.

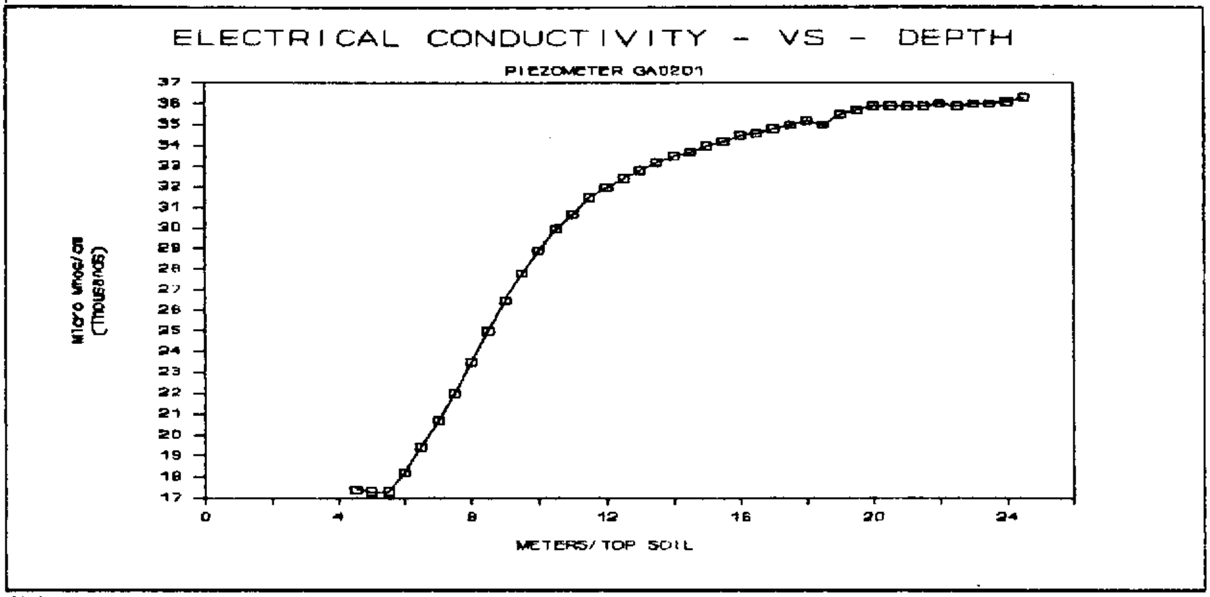


Figure 8 Piezometer GA0201 - Electrical conductivity (µS/cm) vs. depth (m)

The depths at which the measurements were made were not noted in the field. As illustrated in figure 8, the error associated the depth of measurement could be as much as 100%.

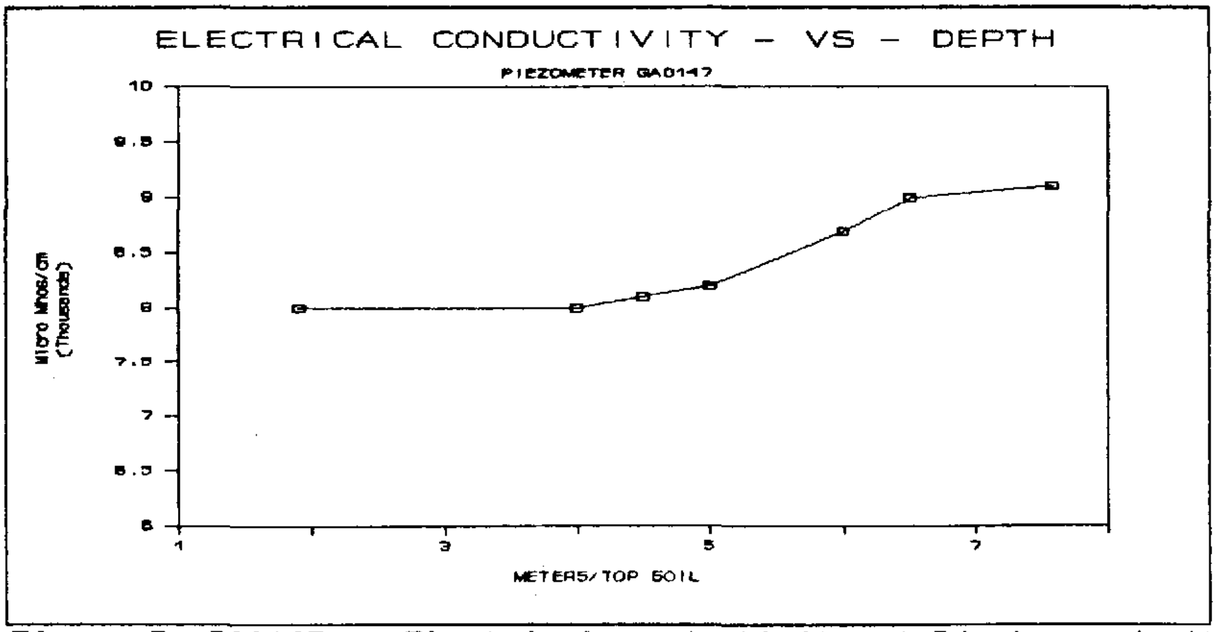


Figure 9 GA0147 - Electrical conductivity (μS/cm) vs depth (m)

Because of the uncertainty in the electrical conductivity measurements for the delta, two statistical tests were made on the seasonal sample data:

1) the "Wilcoxon Rank-Sum test"[47] permits one to determine if the seasonal samples (June 88, October 88, June 89 and October 89) could represent the same population (have the same mean), with a 95% confidence level.

2) the "Wilcoxon Signed-Rank test"[48] permits one to determine if two samples, which could represent the same population, have similar distributions, with a 95% confidence level.

Samples which represent the same population, and which have the same distribution, will contain the most significant electrical conductivity data for the delta.

6.4.1 Wilcoxon Rank-Sum Test

The seasonal samples (June 88, October 88, June 89 and October 89) were tested in order to determine if they represent an identical population. The test which was used (Wilcoxon Rank-sum Test) is based on the following equation:

$$Z = (W - \mu_W)/\sigma_W$$

where:

W = after assignment of ascending ranks to all combined data (sample #1 plus sample #2), the sum per sample of assigned ranks.

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[47] Anderson and other, 1986, p. 589.

[48] Anderson and other, 1986, p. 597.

$\mu_w = n_1 * (n_1 + n_2 + 1)/2$

$\sigma_w = [n_1 * n_2 * (n_1 + n_2 + 1)/12]^{\frac{1}{2}}$

The values of Z which result from the test are shown in the table below. Z values between -1.96 and 1.96 indicate 95% confidence levels.

Table #9: Wilcoxon Rank-Sum Test - Seasonal Z values

MONTH	JUNE_88	OCT_88	JUNE_89	OCT_89
JUNE_88	-	-2.87	-1.55	-1.37
OCT_88	-2.87	-	1.02	0.79
JUNE_89	-1.55	1.02	-	0.05
OCT_89	-1.37	0.79	0.05	-

The month of June 1988 does not satisfy the condition and, consequently, is not representative of the same population as the other seasonal samples (October 88, June 89 and October 89). The month of June 88 corresponds to the establishment of the electrical conductivity field measurement procedures for all the observation points (wells and piezometers).

6.4.2 Wilcoxon Signed-Rank Test

The second test was to determine if the seasonal samples (October 88, June 89) have similar distributions.

This test was made on the aforementioned samples, first for data from wells and piezometers, then from piezometers only:

sample	October 1988	June 1989
1	wells + piezometers	wells + piezometers
2	piezometers only	piezometers only

The difference between the electrical conductivity values (µS/cm October 88 - µS/cm June 89) from the same sites were tested with the Wilcoxon method. At the 95% confidence level, the test results indicate that samples numbered 1 in the table above came from the same population and that samples numbered 2 came from the same population (aquifer).

6.4.3 Electrical conductivity - differentiation by compartment

The electrical conductivity data for the month of June 1989 were used to illustrate the differences between the aquifer's upper and lower compartments. Table #10 indicates the distributions of electrical conductivity values, by category of 5000 µS/cm, for the upper and lower compartments.

The number of values for the upper compartment (146) is not the same as in table #8 (185) because some data were eliminated by the Wilcoxon statistical test (section 6.4.2). The test paired the data by measurement site for the two seasons (October 88 and June 89). Unpaired data (measurement made at a site for only one of the seasons) were eliminated.

The two samples (aquifer upper and lower compartments for June 89) were tested with the Wilcoxon Rank-sum test[49] to see if they could represent the same population (have the same mean).

[49] Anderson, 1986, p. 592.

Table #10: June 89 - Distribution of electrical conductivity values in the aquifer's upper and lower compartments

CONDUCTIVITY CATEGORY			UPPER	LOWER
0	to	5000	45.89%	59.49%
5000	to	10000	14.38%	13.92%
10000	to	15000	13.70%	11.39%
15000	to	20000	10.27%	3.80%
20000	to	25000	0.68%	0.00%
25000	to	30000	0.68%	0.00%
30000	to	35000	0.00%	0.00%
35000	to	40000	2.05%	2.53%
40000	to	45000	3.42%	0.00%
45000	to	50000	2.74%	2.53%
50000	to	55000	1.37%	2.53%
55000	to	60000	0.68%	2.53%
60000	to	65000	2.05%	0.00%
65000	to	70000	0.68%	0.00%
70000	to	75000	0.00%	0.00%
75000	to	80000	0.68%	0.00%
80000	to	85000	0.68%	1.27%
85000	to	90000	0.00%	0.00%
90000	to	95000	0.00%	0.00%
95000	to	100000	0.00%	0.00%
BEYOND			0.00%	0.00%

The essential statistics concerning the electrical conductivity values for the aquifer's upper and lower compartments are:

STATISTICS	upper	lower
NUMBER	146	79
MIN.	165	85
MAX.	82800	81180
AVERAGE	13136	9881
STD. DEV.	17594	16332
MEDIAN	5950	2700

The Wilcoxon (Rank-Sum) test indicates that the value of Z is 3.92.

We can conclude, therefore, with a 95% confidence level, that the two samples do not represent the same population because the Z value (3.92) is not between -1.96 and +1.96. The water in the aquifer's upper compartment is more conductive (saline) than that in the lower compartment (concentration of salts by soil leaching, evaporation and evapotranspiration).

6.4.4 Cartographic treatment of the electrical conductivity data

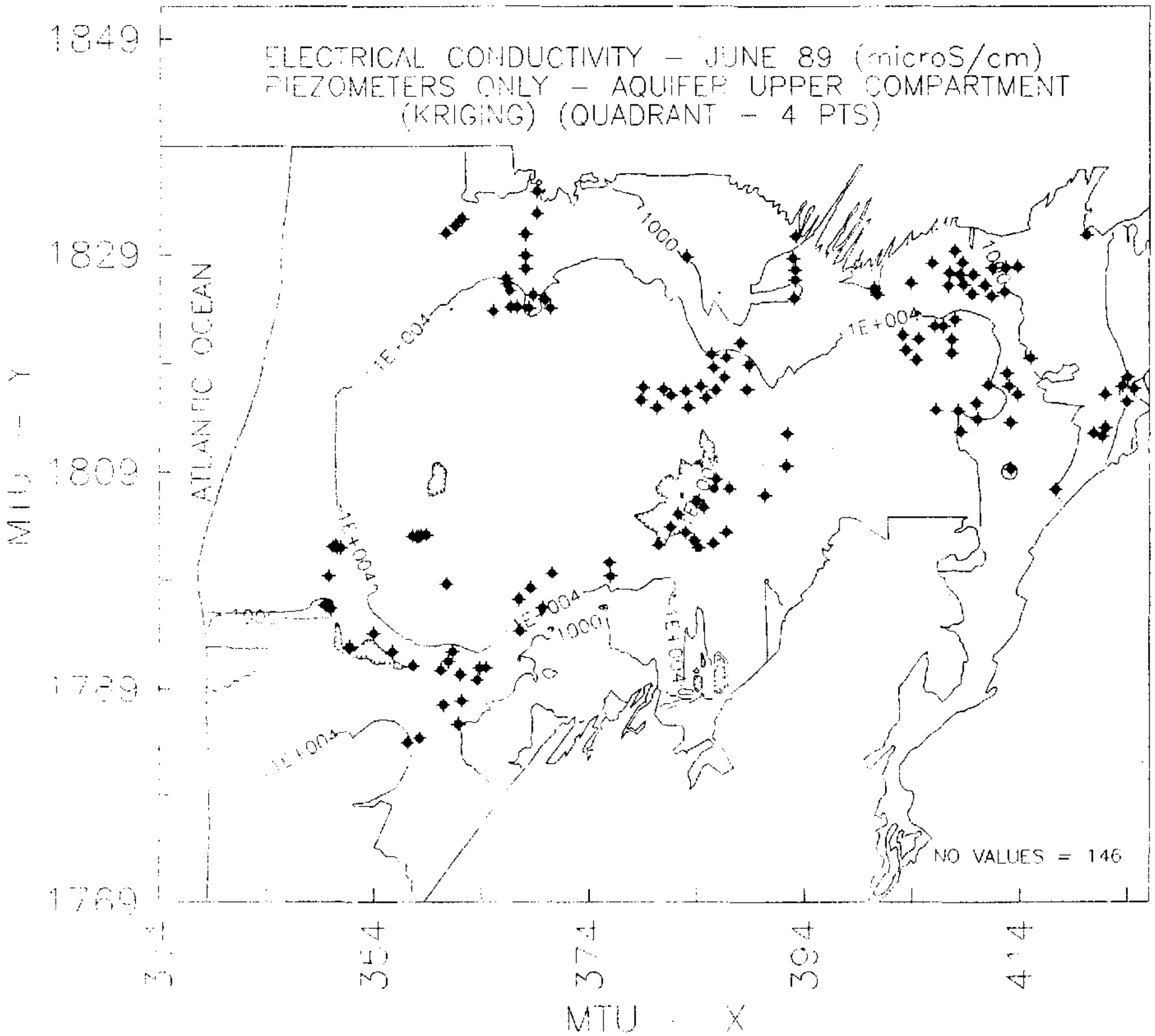
On the following page, the reader will find map #26 "Electrical conductivity - June 89 (µS/cm) - piezometers only - aquifer upper compartment (co_8906t)", which indicates equal value contours for 1000 and 10000 µS/cm of electrical conductivity, representative of the aquifer's upper compartment.

Only measurements from piezometers were used to make the map because the wells sites are preferentially selected by the villagers for fresh water production (not randomly selected). Consequently, a representation of the actual distribution of electrical conductivity of the groundwater in the aquifer's upper compartment is best given by values of electrical conductivity from piezometers.

SENEGAL RIVER - DELTA REGION

SCALE : = 10 Km

MAP Nº 26



This map indicates zones of low electrical conductivity along a North-South axis passing through Lac de Guiers and the town of Rosso as well as near the northern and southern Ouallo/Dieri limits. These low conductivity zones surround a zone of high electrical conductivity in the central part of the delta. Discussion of seasonal or spatial variations in electrical conductivity is not considered worthwhile in light of the poor quality of the field measurement data, as previously explained. The field measurement imperfections are limited to the delta.

Table #11 lists the mathematical relationships[50] between the electrical conductivity and T.D.S. (total dissolved solids) values. Use of these equations with the electrical conductivity values for the month of October 88 permitted the development of map #27 "TDS (calculated) - Total Dissolved Solids (mg/l) - October 88 (based on electrical conductivity) (tds_8810)". This map can be compared to map #15 - TDS for the period 1987-1988, which was developed from laboratory analysis results.

Table #11: Electrical conductivity/mineral content relationships

CONDUCTIVITY (µS/cm) X CONSTANT = MINERAL CONTENT (mg/l)

µS/cm				
CONDUCT. <50	X	1.365079	=	MINERAL CONTENT (mg/l)
50< CONDUCT. <166	X	0.947658	=	MINERAL CONTENT (mg/l)
166< CONDUCT. <333	X	0.769574	=	MINERAL CONTENT (mg/l)
333< CONDUCT. <833	X	0.715920	=	MINERAL CONTENT (mg/l)
833< CONDUCT. <10000	X	0.758544	=	MINERAL CONTENT (mg/l)
10000< CONDUCT.	X	0.850432	=	MINERAL CONTENT (mg/l)

The two data sets (TDS-laboratory and TDS-calculated with table #11 equations for October 88) were tested to see if they represent the same population Wilcoxon Rank-sum Test[51] (see section 6.4.2).

The essential statistics concerning the laboratory and calculated TDS values are:

STATISTICS	TDS_LABO	TDS_CALC
NUMBER	74	192
MIN	195	104
MAX	50490	42522
AVERAGE	14176	10511
STD. DEV.	15135	11431
MEDIAN	7980	5310

The Z value calculated with the Wilcoxon test is 1.81.

We may conclude, with a 95% confidence level, that the two samples represent the same population. Therefore, the electrical conductivity field measurements may validly be used to develop a map of Total Dissolved Solids (mg/l), based on the mathematical relationships shown in table #11. (see map #27 on the next page).

Map #27 corroborates map #15 (TDS) which was developed from laboratory results. It indicates the existence of fresh water zones (TDS values of 1000 mg/l) on the north and south borders of the delta, a brackish water zone (1000 mg/l < 10,000 mg/l) between the Dieri and the central part of the delta, and a saline water zone (TDS > 10,000 mg/l) in the central part of delta which coincides with the river channel during the Inchirrian epoch (see annex #3, Inchirrian sediments, structure contour map of the upper surface).

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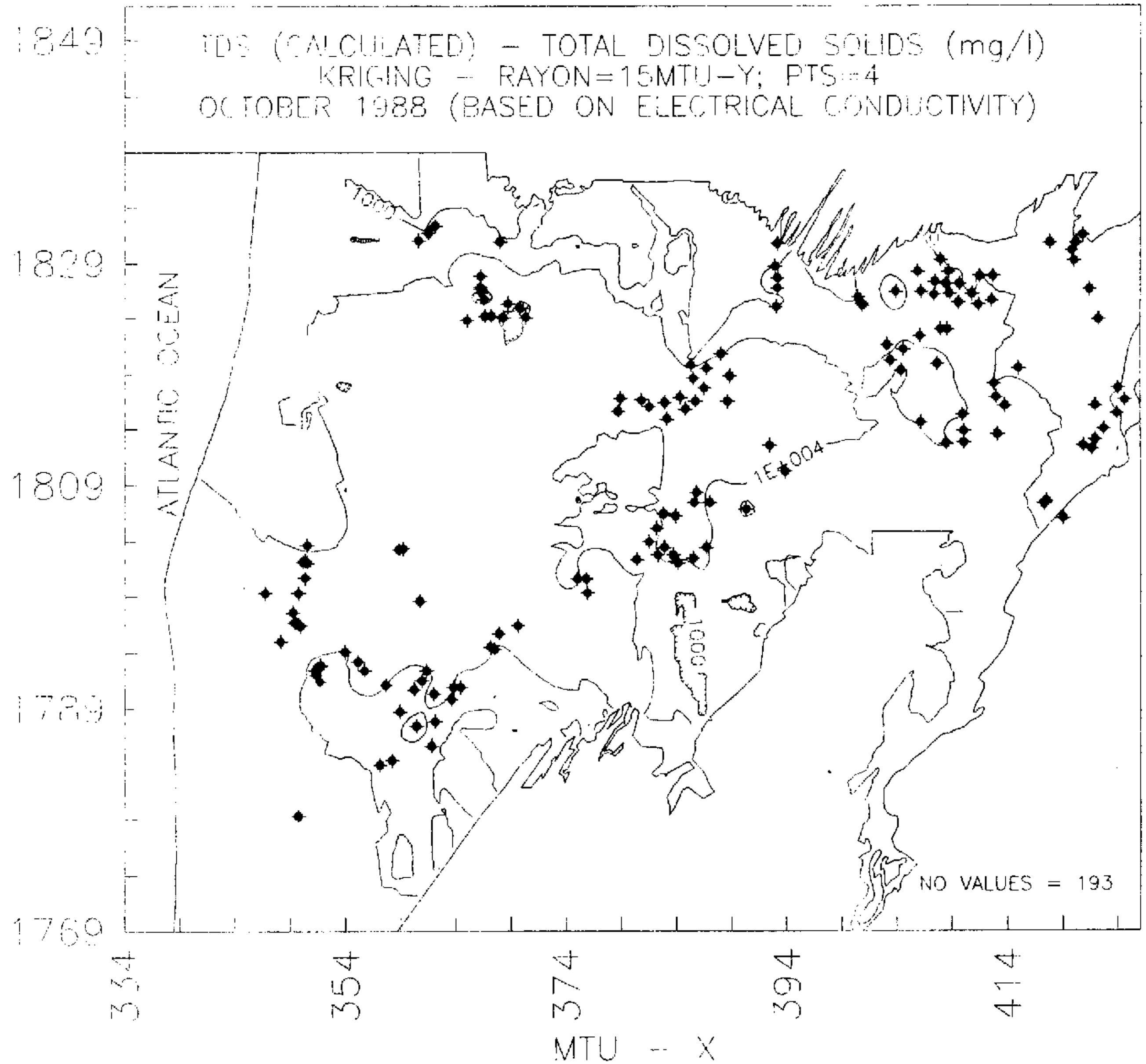
[50] Rodier, p.65.

[51] [illegible]

SENEGAL RIVER - DELTA REGION

SCALE : ⎣______⎦ = 10 Km

MAP Nº 27



7 EVALUATION OF RECHARGES AND LOSSES (for year of 1988)

This chapter deals with groundwater recharge and flow within the limits of the delta. Two schemes were proposed by Filippi[52]. These are:

* vertical water movements: rainfall infiltration (inflow) and evaporation (outflow) within the confines of the delta,

* horizontal water movements: infiltration through the banks of watercourses and canals.

The flatness of the land and the constantly negative potentiometric surfaces (~-0.7 m ASL in June 88, and ~-0.2 m ASL in October 88), except along watercourses and inside irrigated perimeters (~-0.3 m ASL in June 88 and ~+0.4 m ASL in October 88) are not conducive to horizontal percolation of groundwater (see section 6.2 of this report).

Filippi identified the infiltration and exfiltration mechanisms from piezometric observations made by Audibert in 1969 (6 month flood period) in the vicinity of Roncq and Diaouar on the left bank. Then, with the BRGM model (VTD1), modified to incorporate an evaporation function, he reconstructed the 1969 piezometric profiles in order to determine the river-water table relationship. He used the following hydraulic parameters in his calculations: hydraulic conductivity, $K=2.0 * 10^{-3}$ m/s and storage coefficient, $S=4 * 10^{-2}$.

The project considers these values to be too high. The values proposed by the project are: $K_H = 4.4 * 10^{-4}$ cm/sec +/- $K_V = 4 * 10^{-4}$ cm/sec and $S=4 * 10^{-4}$. The values used with the BRGM model, greater than ours, led to an overestimation of the distance to which the river influences the water table, and gave credibility to the safety factor used by Filippi (f=2).

The BRGM model, proposed by Vandenbeusch, was not available to the project, thus an evaluation of the phenomena could not be made in the same way. On the other hand, the monitoring of 7 transverse piezometer lines (annex #8, figures 1 to 6), situated on both banks of the river, during 1988 and 1989, permitted direct observation of piezometric profile fluctuations between the river and the large irrigated perimeters (annex #8, figure 5 and annex #9, figures 2 and 4).

The following chapter sections present a theoretical discussion of the current phenomena, allowing one to evaluate the relative importance of each phenomenon (infiltration, evaporation) individually (not inter-related).

7.1 Inflow from rainfall and irrigation

An estimation of the total annual inflow to the aquifer from water infiltration (rainfall and irrigation) was attempted for the delta for the year 1988 by examination of the maps "Water table variations between June and October 88" (see maps #22, #23).

Here are a few useful reminders pertaining to reference year 1987[53]:

1) for the reference year, the cultivated land area (SC) was 102.7 km^2 [54].

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[52] Filippi, 1984, chap. 2.2, p. 6.

[53] From the OMVS/CEPC data base.

[54] Ref.: PES, 1989, p. 23 and 25, delta region.

2) the rate of increase[55] of the net irrigable area (SNI) was about 7% for the right and left banks of the Senegal River, for the period 1975 - 1987. This rate is applied to the cultivated land area (SC) of 19987 in order to estimate the corresponding area for the year 1988.

3) the theoretical water requirements for rice production (global water needs) per unit of land area, for the different agricultural seasons, and for various soil types[56] are summarized in table #12:

Table #12: Global water requirements (rice production)

CROPPING SEASON	CYCLE DAYS	GLOBAL WATER REQUIREMENTS (1)	(2)	M3/HA (3)
HIV	95	8,400	11,200	13,400
CSC	120	13,500	18,100	21,800
CSF	155	13,900	19,000	23,200

LEGEND

CODE	SOILS	TYPICAL GRANULOMETRY
(1)	HOLLALDE	55 % < % CLAY
(2)	FAUX HOLLALDE	30 % < % CLAY < 55 %
(3)	FONDE	% CLAY < 30%

The table above describes the global water requirements for rice (net requirements + losses). "The net water requirements of crops grown according to the production calendar depend only on the variety planted (development stage, anatomy, physiology, color, expected production) and the climate (humidity, temperature, wind, sunshine...). The global water requirements (net requirements + losses) depend, as well, on the irrigation system (gravity, pressurized, sprinkler, drip, ...) and soil type (% clay, impermeable layer) which affect water losses (percolation, evaporation, diffusion...)."[57]

4) the distribution of cultivated soils for the entire Senegal River valley, per bank[58] is as follows:

* for the left bank,
  * 59 % soils HOLLALDE
  * 24 % soils FAUX HOLLALDE
  * 17 % soils FONDE
* for the right bank,
  * 53 % soils HOLLALDE
  * 21 % soils FAUX HOLLALDE
  * 26 % soils FONDE

This distribution is considered representative of the delta.

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[55] Ref.: PES, 1989, p. ii.

[56] Dachraoui, page 17.

[57] Dachraoui, p. 17.

[58] Ref.: PES, 1989, p.38.

5) for this[59] distribution of soils (estimation for 1987), the estimated volume of water necessary for irrigated rice production in the delta during the rainy season (assuming that 100% of the cultivated land area is in rice production) is 9.77E+07 m^3. This volume of water corresponds to a height of water of 951 mm, to which is added the precipitation (242 mm in 1988), for a grand total of 1193 mm within the limits of the large irrigated perimeters.

An evaluation of the volume of water infiltrating the aquifer (V_r = effective aquifer recharge) is estimated with the following formula:

$$V_r = A * Dh_{max} * S$$

where:

A = surface area concerned by the evaluation (km^2)

Dh_{max} = maximum water table rise (m), deduced from the maps of water table and potentiometric surface variations, June-Oct 88 - (inside and outside the perimeters)

S = coefficient of storage (dimensionless)

This formula can be applied to unconfined aquifer zones (water tables) (V_{ru}) and confined aquifer zones (V_{rc}) inside and outside the irrigated perimeters.

The percentages of the delta land area corresponding to confined aquifer zones (A_c) and to unconfined aquifer zones (A_u) vary with the seasons and are listed in section 6.3 of this report.

The values of the coefficient of storage, S, are: 4*10-4 for confined aquifer zones (see section 5.1.2) and 0.15 for unconfined aquifer zones (corresponding to average theoretical values (S) for fine-grained sands and silts) (see section 5.1.2).

Table #13: Estimation of surface infiltration in irrigated zones (ip)

total area (SB)	4343.8	km^2
cultivated area (SC)	102.7	km^2 = 1987
cultivated area (SC)	109.9	km^2 = 1988
water table area (A_u)	45.00%	of dry season[60] area (SB)
confined aquifer area (A_c)	55.00%	of dry season area (SB)

The area of the delta having a shallow aquifer subject to rainfall infiltration is 3883 km^2. This corresponds to:

$$A_r = SB - (A_g - A_{sen} - A_{div} - SC)$$

[59] Ref.: PES, 1989, p.35.

[60] See section 6.3 of this report. For the calculations, we consider that the area percentages Al and Ac are the same inside and outside the perimeters.

where:

Total area	(SB)	= 4348.8	km^2	
Cultivated area	(SC)	= 109.9	km^2	
Area[61] Lac de Guiers	(A_g)	= 275	km^2	(if Z = 1.80 m ASL)
Area[62] Senegal River	(A_{sen})	= 51	km^2	
Area watercourses	(A_{div})	= 30	km^2	= approximation

DELTA REGION		Dh_{max} (m)	S	V_{r_ip} m^3	$(V_{r\_ip})/(V_{t\_ip})$ %	T_{r_ip} mm/jr
ZONES		1988		$(A*Dh_{max}*S)$		
WATER TABLE	(V_{ru_ip})	0.70	1.50E-01	5.19E+06	3.96%	
CONFINED AQUIFER	(V_{rc_ip})	0.47	4.00E-04	1.14E+04	0.01%	
TOTAL	(V_{r_ip})	NA	NA	5.20E+06	3.97%	0.50

Table #14: Estimation of shallow infiltration in non-irrigated zones (op)

DELTA REGION		Dh_{max} (m)	S	V_{r_op} m^3	$(V_{r\_op})/(V_{t\_op})$ %	T_{r_op} mm/jr
ZONES		1988		$(A*Dh_{max}*S)$		
WATER TABLE	(V_{ru_op})	0.47	1.50E-01	1.20E+08	13.14%	
CONFINED AQUIFER	(V_{rc_op})	0.34	4.00E-04	2.82E+05	0.03%	
TOTAL	(V_{r_op})	NA	NA	1.20E+08	13.17%	0.53

The columns marked $(V_{r\_ip})/(V_{t\_ip})$ in table #13 and $(V_{r\_op})/(V_{t\_op})$ in table #14 indicate the percentage volume infiltrated water with regard to the total volume (V_t) available for the case considered: irrigated zones (V_{t_ip} = 1.31E+08 m^3, non-irrigated (V_{t_op} = 1.02E+09 m^3).

Thus:

* in irrigated zones (water table), 3.96% of the total volume (rainfall + irrigation) joined the water table by vertical infiltration. This represents 47.2 mm of the 1193 mm available. If we assume an agricultural cycle of 95 days, the rate of vertical infiltration (T_{r_ip}) would be 0.5 mm/day.

* in non-irrigated zones (water table), 13.14% of the total volume (rainfall) joined the water table by vertical infiltration. This represents 31.8 mm of the 242 mm available. If we assume an infiltration period (number of days of rainfall and ponding) of 60 days, the rate of vertical infiltration (T_{r_op}) would be 0.53 mm/day.

* in irrigated and non-irrigated zones (confined aquifer), less than 0.03% of the total available volume joined the aquifer.

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61 See section 2.1 of this report.

62 See annex #1, of this report (length X average width).

These numbers reveal the aquifer's capacity to store a real volume of water.

In a water table zone (unconfined aquifer) the unsaturated volume, corresponding to the effective porosity, is capable of storing available water. Access to this storage zone is controlled by the vertical hydraulic conductivity and the volumes stored are a function of time. The stored water is generally fresh or weakly mineralized and constitutes a temporary reservoir before being lost through evaporation.

In a confined aquifer zone, the aquifer does not effectively store more water but rather the hydrostatic pressure inside of it increases with the ambiant conditions, regardless of time.

7.2 Inflow - lateral infiltration through river and watercourse banks

The seasonal horizontal hydraulic gradient for the period 1988-1989 was investigated through 6 piezometer lines, transverse to the banks of the Senegal River, on both the right and left banks. These lines are coded L1 to L7 (see map #4 localizing the OMVS network points, section 3.5).

These lines are described in term of MTU-X and MTU-Y coordinates in annex #8. The corresponding geological sections are in annex #4B.

The spacing between piezometers along these lines is short (metric) and the maximum perpendicular distance of hydrogeological observation from the banks of the Senegal River is less than 5 kilometers and generally less than 3 kilometers, i.e., twice the theoretical influence length as calculated in the simulation done by Fillipi, 1984.

Except for line L1, the hydraulic gradients apply to the aquifer's upper compartment.

The seasonal piezometric profiles are included in annex #8, figures 1 to 7). The profiles indicated in these graphics were calculated by the computer following geostatistical treatment (Kriging) of the field measurements. The number of observation points located on or near the piezometer lines is indicated in table #15. This table also presents information about the hydraulic conductivity at each of these observation points, their position (km) along the X axis and their intake depths. These graphics result from the combined use of Surfer and Grapher software.

The ordinates of the graphs in annex 10 correspond to hydraulic head. The abscissas correspond to distance from the river and the O (zero) value coincides with the hydraulic head measured in the center of the Senegal river bed for the season concerned. The ground surface topographic profiles (from the topographic maps in section 2.2) are superimposed on the piezometric profiles.

All these profiles (piezometric and topographic) reflect the geostatistical reality without being completely exact.

Table #15 lists the piezometers related to each piezometer profile (L1 to L7) as well as their respective distances from the center of the Senegal River, Table #15: List of piezometers by piezometer line (L1 A L7)

LINE #	PIEZO #	MTU-X	MTU-Y	ELEV m ASL	DIST KM	INTAKE DEPTH	KK Cm/sec
L1	GA0021	351.7	1792.9	3.70	0.10	13.00	>1.0E-3
L1	GA0022	351.7	1792.8	3.01	0.13	19.00	>1.0E-3
L1	GA0023	351.7	1792.8	3.05	0.13	13.00	1.1E-3
L1	GA0025	351.3	1792.0	3.93	0.80	21.00	6.5E-4
L1	GA0026	351.3	1792.0	3.91	0.80	14.00	3.1E-4
L1	GA0027	351.6	1791.4	4.22	1.50	14.00	N/I
L1	GA0028	351.7	1790.9	4.83	2.00	17.00	N/I
L2	DA015	348.8	1796.5	1.77	2.80	5.00	>1.0E-3
L2	DA016	349.0	1796.4	1.63	2.70	6.00	>1.0E-3
L2	DA017	349.2	1796.3	1.63	2.60	6.00	>1.0E-3
L2	DA018	349.5	1796.2	1.60	2.50	6.00	>1.0E-3
L3	DA019	350.1	1802.1	3.02	3.50	7.02	3.1E-4
L3	DA020	350.3	1802.1	2.60	3.30	6.86	>1.0E-3
L3	DA021	350.5	1802.0	1.51	3.10	7.00	1.1E-3
L3	DA022	350.8	1802.0	1.45	2.80	5.50	1.0E-3
L4	GA0012	357.9	1803.0	1.38	0.23	5.15	2.1E-5
L4	GA0014	358.1	1803.0	1.39	0.28	4.86	7.8E-5
L4	GA0015	358.3	1803.1	1.53	0.50	5.05	7.8E-5
L4	GA0017	357.5	1803.1	1.41	0.82	4.99	2.9E-4
L4	GA0018	358.8	1803.2	1.33	1.25	5.00	>1.0E-3
L5	GA0034	366.3	1826.3	0.92	1.20	9.95	1.8E-4
L5	GA0037	366.2	1826.8	2.11	0.43	7.95	>1.0E-3
L5	GA0039	366.5	1825.7	0.92	0.46	10.46	3.4E-5
L7	DA059	400.6	1825.5	3.15	0.40	5.00	>1.0E-3
L7	DA060	400.4	1825.9	3.53	1.10	5.00	>1.0E-3
L7	DA061	400.7	1825.3	2.28	0.20	5.00	>1.0E-3

Table #16 lists for each of the lines (L1 to L7), by season, the type of aquifer in which the fluctuations were observed, the thickness of the clay layer covering the aquifer (if there is one), the water level of the river, the distance to which the watercourse was observed to influence the adjacent aquifer, and the granulometric description of the formation tapped (dominant class only).

The distance from the banks of the river to which the river's water level has an influence, as observed in the field, corresponds to the distance at which the hydraulic gradient Dh(June) is about equal to Dh(October) or else the distance at which v_n (June) is about equal to v_n (October).

Table #16: Transverse piezometer lines

# LINE	BANK	SEASON	TYPE AQUIFER	m ASL RIVER	m/km I hor	km INFLUENCE	WATER ELEVATION DRY	RAINY	AQUIFER	CODE GEOL	GRANULOMETRY	CLAY THICK(M)
L1	LB	06/88	UNCONFINED	0.39	1.68	2.5	-2.6	-2.4	LOWER	IN	FINE SAND	0
L1	LB	10/88	UNCONFINED	0.97	1.96	2.5	-2.6	-2.4	LOWER	IN	FINE SAND	0
L1	LB	06/89	UNCONFINED	0.30	2.10	2.0	-2.6	-2.4	LOWER	IN	FINE SAND	0
L1	LB	10/89	UNCONFINED	1.92	2.20	2.0	-2.6	-2.4	LOWER	IN	FINE SAND	0
L2	RB	06/88	CONFINED	0.39	0.05	1.9	-0.2	0.2	UPPER	NK	FINE SAND	2
L2	RB	10/88	CONFINED	0.97	0.33	2.0	-0.2	0.2	UPPER	NK	FINE SAND	2
L2	RB	06/89	CONFINED	0.30	0.20	2.4	-0.2	0.2	UPPER	NK	FINE SAND	2
L2	RB	10/89	CONFINED	1.92	1.00	2.0	-0.2	0.2	UPPER	NK	FINE SAND	2
L3	RB	06/88	UNCONFINED	0.39	0.19	3.2	-0.2	0.2	UPPER	NK	MEDIUM SAND	0
L3	RB	10/88	UNCONFINED	0.97	0.37	2.7	-0.2	0.2	UPPER	NK	MEDIUM SAND	0
L3	RB	06/89	UNCONFINED	0.30	0.20	3.4	-0.2	0.2	UPPER	NK	MEDIUM SAND	0
L3	RB	10/89	UNCONFINED	1.92	1.10	2.0	-0.2	0.2	UPPER	NK	MEDIUM SAND	0
L4	LB	06/88	CONFINED	0.39	0.00	0	NA	NA	UPPER	NK	FINE SAND	2
L4	LB	10/88	CONFINED	0.97	NOT MEASURED; FLOODED				UPPER	NK	FINE SAND	2
L4	LB	06/89	CONFINED	0.30	0.00	0	NA	NA	UPPER	NK	FINE SAND	2
L4	LB	10/89	CONFINED	1.92	NOT MEASURED; FLOODED				UPPER	NK	FINE SAND	2
L5	LB	06/88	CONFINED	0.39	0.60	1.0	-0.2	0.3	UPPER	NK	FINE SAND	2
L5	LB	10/88	CONFINED	0.97	0.80	1.0	-0.2	0.3	UPPER	NK	FINE SAND	2
L5	LB	06/89	CONFINED	0.30	0.50	1.0	-0.2	0.3	UPPER	NK	FINE SAND	2
L5	LB	10/89	CONFINED	1.92	1.70	1.0	-0.2	0.3	UPPER	NK	FINE SAND	2
L7	RB	06/88	UNCONFINED	0.39	0.00	1.1	0.3	0.3	UPPER	NK	MEDIUM SAND	0
L7	RB	10/88	UNCONFINED	1.60	1.45	1.1	0.3	0.3	UPPER	NK	MEDIUM SAND	0
L7	RB	06/89	UNCONFINED	0.30	0.00	1.1	0.3	0.3	UPPER	NK	MEDIUM SAND	0
L7	RB	10/89	UNCONFINED	1.92	1.74	1.1	0.3	0.3	UPPER	NK	MEDIUM SAND	0

From this table, we may conclude that:

1) regardless of season, during the period of observation 1988-1989, the horizontal hydraulic gradient was always positive, i.e., oriented from the river towards the adjacent aquifer. Within the confines of the delta, as seen from piezometer installations L1 through L7, the aquifer does not contribute to the river flow.

2) the distances (perpendicular to the river bed) to which the river influences any piezometer line, are constant, regardless of season.

3) depending on the piezometer line, these influence distances vary from 1 to 2.5 kilometers, except for lines L2 and L3 for which a ponding zone (about 2 kilometers) separates the river from the piezometers.

3) the horizontal hydraulic gradients in the zones influenced by the river vary from 0 to 2.20 m/km.

7.2.1 Horizontal interstitial flow velocity

The sediments tapped by the OMVS piezometer network have low values of hydraulic conductivity. The horizontal flow velocities were calculated with the following formulas[63]:

$$v_n = q/n$$

where:

v_n = average interstitial flow velocity (m/year)
q = specific discharge or Darcy velocity (m/year)
n = effective porosity, or specific yield in unconfined aquifers, (dimensionless)

$$q=-K*Dh$$

where:

K = hydraulic conductivity (cm/sec)
Dh = hydraulic gradient (dimensionless)

The range of possible values of K[64] and Dh[65] in the limits of the delta are presented below. The range of hydraulic gradient values is suitable for the right and left banks of the river and of its sloughs. Elsewhere in the delta, the hydraulic gradients are practically null, thus the horizontal flow velocities can be considered null.

K	values units	Dh	values m/km
K min	1.00E-05 cm/sec	$Dh_{0.5}$	0.5 m/km
$(K_\mu - K_\sigma)$	4.00E-05 cm/sec	$Dh_{1.0}$	1.0 m/km
K_μ	4.40E-04 cm/sec	$Dh_{1.5}$	1.5 m/km
$(K_\mu + K_\sigma)$	8.40E-04 cm/sec	$Dh_{2.0}$	2.0 m/km
Kmax	1.00E-03 cm/sec	$Dh_{2.5}$	2.5 m/km

Tables #17 through #19 show the v_n (m/year) values calculated for various porosities:

Table #17: average interstitial flow velocity v_n (m/year), if n = 0.08 (silt)

parameters	K min	$(K_\mu - K_\sigma)$	K_μ	$(K_\mu + K_\sigma)$	Kmax
$Dh_{0.5}$	0.02	0.08	0.87	1.66	1.97
$Dh_{1.0}$	0.04	0.16	1.73	3.31	3.94
$Dh_{1.5}$	0.06	0.24	2.60	4.97	5.91
$Dh_{2.0}$	0.08	0.32	3.47	6.62	7.88
$Dh_{2.5}$	0.10	0.39	4.34	8.28	9.86

63 Ref.: Todd, 1980, p. 67.

64 See section 5.1.1 of this report.

65 See annex 8, piezometric profiles coded L1 to L7.

Table #18: average interstitial flow velocity v_n (m/year), if $n = 0.15$ (sand and silt)

parameters	K min	$(K_\mu - K_\sigma)$	K_μ	$(K_\mu + K_\sigma)$	Kmax
$Dh_{0.5}$	0.01	0.04	0.46	0.88	1.05
$Dh_{1.0}$	0.02	0.08	0.93	1.77	2.10
$Dh_{1.5}$	0.03	0.13	1.39	2.65	3.15
$Dh_{2.0}$	0.04	0.17	1.85	3.53	4.20
$Dh_{2.5}$	0.05	0.21	2.31	4.42	5.26

Table #19: average interstitial flow velocity v_n (m/year), if $n = 0.23$ (fine grained sand)

parameters	K min	$(K_\mu - K_\sigma)$	K_μ	$(K_\mu + K_\sigma)$	Kmax
$Dh_{0.5}$	0.01	0.03	0.30	0.58	0.69
$Dh_{1.0}$	0.01	0.05	0.60	1.15	1.37
$Dh_{1.5}$	0.02	0.08	0.90	1.73	2.06
$Dh_{2.0}$	0.03	0.11	1.21	2.30	2.74
$Dh_{2.5}$	0.03	0.14	1.51	2.88	3.43

We see from these tables that as the porosity decreases the horizontal flow velocity increases.

The limiting values for hydraulic gradient $Dh_{2.0}$ (corresponding to the flood period or the water level maintained by Diama Dam upon completion of the right bank dike) and for a porosity of 0.15 (value used by the project) are:

$$v_n(\text{Kmin}, Dh_{2.0}, n=0.15) = 0.04 \text{ m/an}$$

$$v_n(\text{Kmax}, Dh_{2.0}, n=0.15) = 4.20 \text{ m/an}$$

7.2.2 Influence distances and volumes of water infiltrating through the riverbanks

The water level fluctuations of the Senegal River and its branches cause piezometric surface fluctuations in the adjacent aquifer.

Todd (1980) proposes the following formulas[66] to evaluate: the relationship (h/h_0) at some distance of influence from the bank, the lag time (t_L) between attainment of the maximum surface water level and the effect on the piezometric surface at some distance from the bank, and the volumes infiltrating per meter of stream bank (V_{s}).

$$h/h_0 = e^{-x(\pi*S/t0*T)^{1/2}}$$

$$t_L = x*(t_0*S/4*\pi*T)^{1/2}$$

$$V = h_0*(2*t_0*S*T/\pi)^{1/2}$$

These equations are based on theory but they permit a good approximation of the phenomena.

The various parameters are illustrated in the following sketch.

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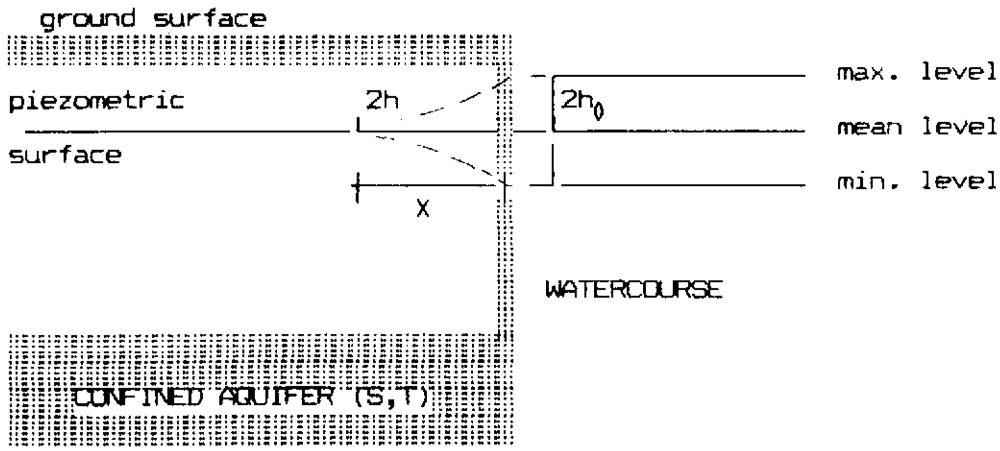
[66] Todd, 1980, p. 242 - 247.



From the sketch and the equations above:

X = orthogonal distance from the bank of the watercourse (m)

h_0 = the amplitude (m) or the half-height of the total surface water level fluctuation (max. level - min. level)

t_0 = period of oscillation of the surface water (days)

S = coefficient of storage (dimensionless)

T = coefficient of transmissivity (m^2/sec)

E = aquifer thickness (m)

t_L = lag time (days)

The hydraulic parameter values used in the calculations (section 5.1.1 and 5.1.2 of this report) are:

E = 8 m [67]
K = 4.00E-04 cm/sec (slug test)
S = 4.00E-04 (hypothetical for confined aquifer)
T = KE = 3.20E-05 m^2/sec

These parameters are the constants in the Todd equations.

The variables in the Todd equations are essentially the parameters X and t_0. The results of the calculations are shown in the double-entry tables #20 to #23.

[67] See map #7 - structure contour map of the aquifer's upper compartment.

Table #20: Values of h/h_0 – vs. – oscillation period

$$h/h_0 = e^{-x(\pi*S/t0*T)^{½}}$$

If t_0 = X (m)	2 days	30 days	120 days
		VALUES	of h/h_0
10	86.01%	96.18%	98.07%
100	22.15%	67.76%	82.31%
1000	0.00%	2.04%	14.28%
2000	0.00%	0.04%	2.04%
3000	0.00%	0.00%	0.29%
5000	0.00%	0.00%	0.01%
10000	0.00%	0.00%	0.00%

Table #21: Lag-time (t_L = days) – vs. – oscillation period

$$t_L = x*(t_0*S/4*\pi*T)^{½}$$

If t_0 = X (m)	2 days	30 days	120 days
		VALUES of t_L	(days)
10	0.05	0.19	0.37
100	0.48	1.86	3.72
1000	4.80	18.58	37.17
2000	9.60	37.17	74.34
3000	14.40	55.75	111.51
5000	23.99	92.92	185.85
10000	47.99	185.85	371.69

Table #22: Volumes of water infiltrating per meter stream bank ($V_{ml} = m^3/m$)

$$V = h_0*(2*t_0*S*T/\pi)^{½}$$

If t_0 = h_0	2 days	30 days	120 days
	VOLUME INFILTRATING (m^3/m)		
0.50	0.02	0.07	0.15
1.00	0.04	0.15	0.29
1.50	0.06	0.22	0.44
2.00	0.08	0.29	0.58
2.50	0.09	0.36	0.73

Table #23: Total volumes of water infiltrating ($V = m^3$)

river length (L) :	115 km
stream bank length (2L):	230 km

$$V = h_0*(2*t_0*S*T/\pi)^{½}*2L$$

If t_0 = h_0	2 days	30 days	120 days
	VOLUME INFILTRATING (m^3)		
0.50	4.32E+03	1.67E+04	3.34E+04
1.00	8.63E+03	3.34E+04	6.69E+04
1.50	1.29E+04	5.01E+04	1.00E+05
2.00	1.73E+04	6.69E+04	1.34E+05
2.50	2.16E+04	8.36E+04	1.67E+05

Though these equations are here shown for the case of a confined aquifer, they may also be applied to an unconfined aquifer if the amplitude of the water table fluctuation is small compared with the aquifer thickness.

The interpretation of the results shown in tables #20 and #21 applies to the case of t_0 = 120 days which corresponds well to the oscillation period observed in 1988 (see figure 1).

Table #20 indicates that for any amplitude of surface water fluctuation, the variation in the piezometric surface will not be greater than 14.28% at a distance of 1 km from the bank, and not more than 2.04% at 2 km. These calculated values are coherent with the influence distances observed in the field from the piezometers lines (see annex #8, fig. L1 to L7, and section 7.2, table #16).

The lag times between when the maximum surface water level is reached and when the maximum piezometric variation is noted are 37 days at 1 km and 74 days at 2 km.

For the same oscillation period (120 days), the volumes of infiltrating water (V_q=m^3/m) vary from 0.15 m^3/m (h_0=0.5m) to 0.73 m^3/m (h_0=2.5m). These values of h_0 correspond to the range of water levels at which the Senegal River might be maintained.

These specific volumes of water (0.15 m^3/m and 0.73 m^3/m) correspond respectively to total infiltrating volumes of 33,400 m^3 and 167,000 m^3 along both banks of the river (maximum width of infiltration corridor is 2 km along each bank). These volumes are negligible and the land area in the influence zone is 330 km^2 , that is, 7.59% of the total delta surface area.

The calculations shown in tables #20 to #23 are only an estimation since:

1) the hydrogeological conditions to which these formulas are here applied do not correspond exactly to the theoretical conditions for which the equations were developed. For example, the piezometric surface is not flat as the theory assumes nor are the surface water level fluctuations exactly sinusoidal.

2) the volumes of water evaporated are not taken into consideration.

In conclusion, the inflows from infiltration to the upper aquifer compartment in the delta (unconfined and confined) are:

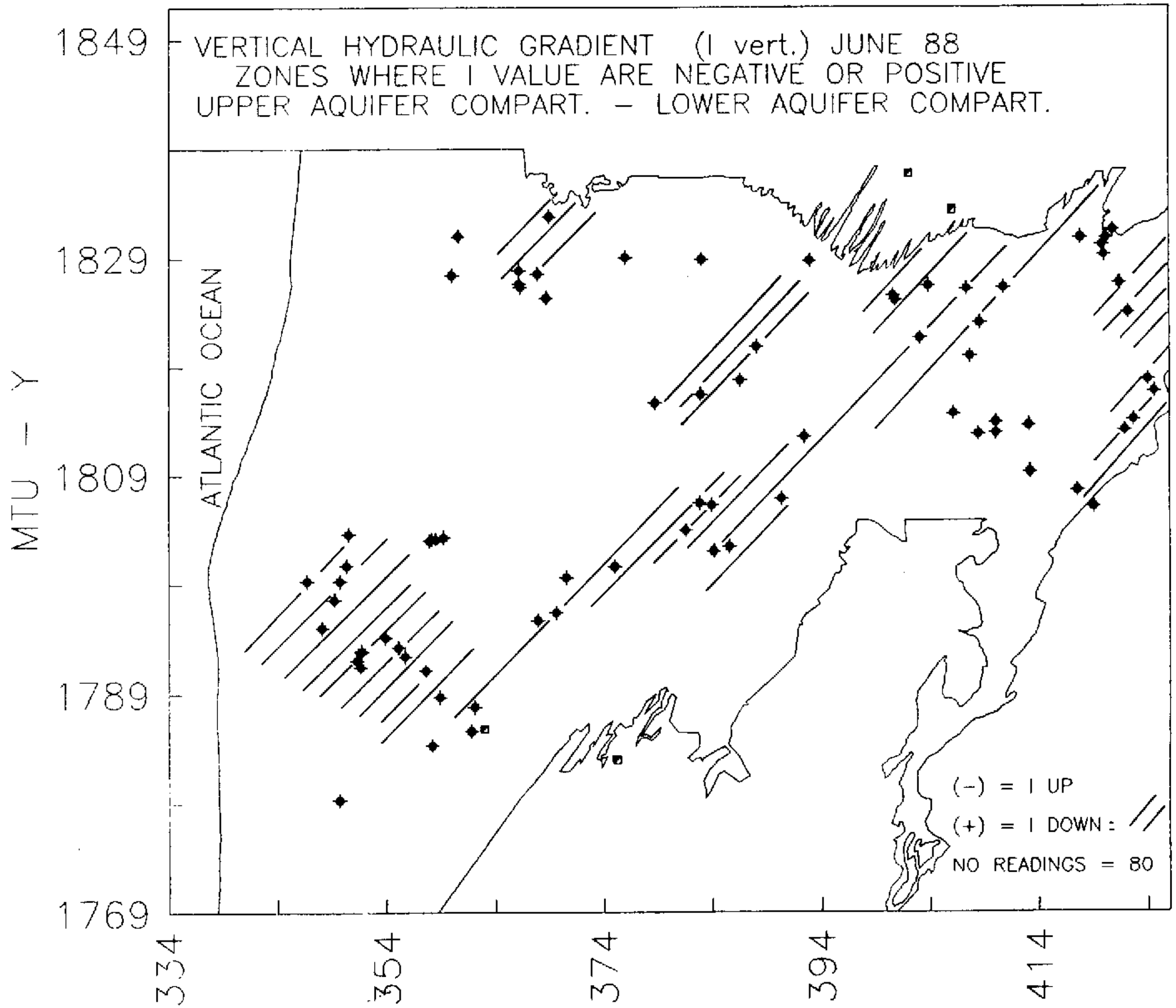
INFLOWS	M^3/an	% Total
RAINFALL + IRRIGATION IRRIGATED ZONES	52.00E+05	4.15%
RAINFALL NON-IRRIGATED ZONES	1200.00E+05	95.72%
STREAM BANK INFILTRATION	1.67E+05	0.13%
TOTAL	1253.67E+05	100.00%

These numbers indicate the preponderance of the vertical inflows to the horizontal inflows in the hydraulic exchanges. Infiltration through the stream banks is insignificant in comparison to infiltration of rainfall. It is important to note that in irrigated zones the infiltration of irrigation water represents 50% of the total calculated infiltration volume. The effectiveness of this source is related to time of application of irrigation water. The increase of agricultural seasons per year will contribute

DELTA REGION – SENEGAL RIVER

SCALE : = 10 Km

MAP Nº 28



SENEGAL RIVER – DELTA REGION

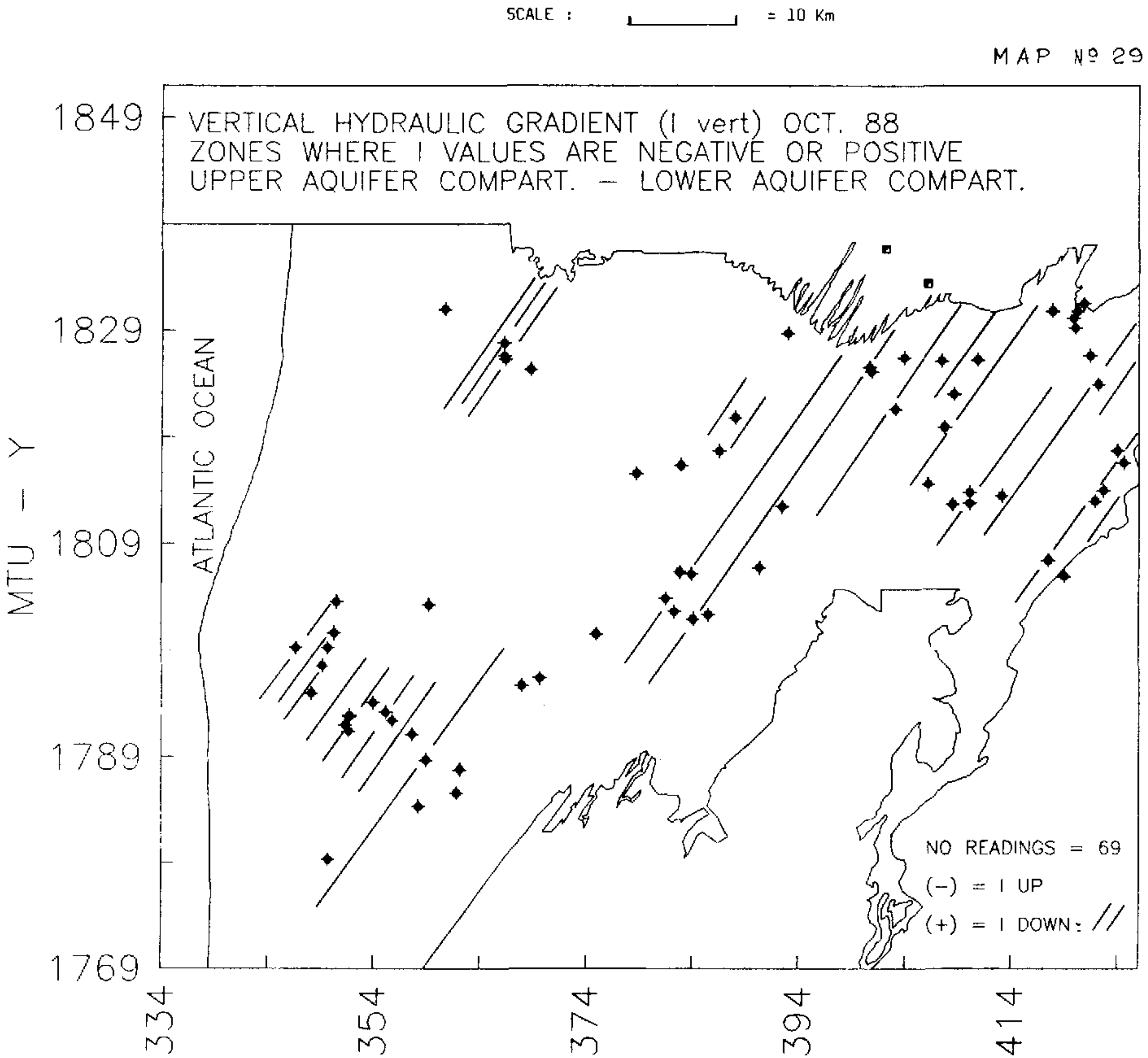


Table #25: List of piezometers by piezometric line (L8 to L12)

LINE #	PIEZO #	MTU X	MTU-Y	ELEV. M (ASL)	DIST. KM	INTAKE DEPTH(M)	KF CM/SEC
L8	DA039	406.2	1827.2	2.28	1.10	12.00	>1.0E-3
L8	DA040	407.5	1827.3	2.82	1.40	5.08	N/I
L8	DA043	408.5	1827.1	2.63	1.70	5.00	2.7E-4
L8	DA044	408.7	1828.2	1.69	2.80	11.00	2.2E-4
L8	DA045	408.8	1826.2	2.50	1.20	7.00	>1.0E-3
L8	DA046	409.7	1827.1	2.77	2.40	7.00	>1.0E-3
L9	DA047	409.6	1825.4	3.04	1.20	7.00	4.4E-4
L9	DA049	410.8	1826.2	1.78	1.30	5.00	>1.0E-3
L9	DA050	411.4	1825.2	2.64	0.20	6.00	>1.0E-3
L9	DA051	411.5	1827.8	1.96	2.80	10.99	N/I
L10	GA0051	388.6	1816.5	1.36	5.00	5.20	N/I
L10	GA0052	384.8	1815.8	1.60	6.00	4.85	4.1E-4
L10	GA0053	385.7	1816.5	1.32	5.50	5.10	1.3E-4
L10	GA0058	384.3	1816.9	1.40	5.50	4.95	>1.0E-3
L10	GA0062	382.9	1816.4	1.63	6.50	5.10	8.6E-4
L10	GA0063	381.5	1816.0	1.74	8.00	5.10	6.5E-5
L10	GA0064	380.8	1816.6	1.83	7.80	5.07	1.8E-4
L10	GA0065	378.9	1816.8	1.29	9.00	5.06	4.2E-5
L10	GA0067	378.7	1815.6	1.08	0.38	4.85	N/I
L11	GA0047	388.0	1820.8	2.13	1.18	5.05	2.2E-4
L11	GA0048	388.0	1820.8	2.11	1.19	4.85	2.3E-4
L11	GA0049	388.0	1820.8	2.04	1.17	5.10	6.6E-4
L11	GA0050	388.8	1818.8	1.31	2.80	5.10	1.6E-5
L11	GA0051	388.6	1816.5	1.36	5.00	5.20	N/I
L11	GA0052	384.8	1815.8	1.60	6.00	4.85	4.1E-4
L11	GA0053	385.7	1816.5	1.32	5.50	5.10	1.3E-4
L11	GA0056	386.5	1817.7	1.90	4.00	5.25	4.1E-5
L11	GA0057	385.5	1818.6	1.34	3.30	5.00	N/I
L11	GA0058	384.3	1816.9	1.40	5.50	4.95	>1.0E-3
L11	GA0059	386.7	1819.5	2.00	2.00	5.08	1.2E-3
L12	GA0100	381.5	1803.9	0.57	1.50	7.95	1.8E-4
L12	GA0102	382.9	1803.4	1.71	2.50	6.90	2.5E-5
L12	GA0104	384.1	1802.0	1.51	4.00	10.00	1.1E-4
L12	GA0105	383.7	1802.7	1.66	3.50	5.10	5.6E-5
L12	GA0106	384.4	1803.8	1.80	4.20	6.95	1.0E-5
L12	GA0108	385.5	1802.4	1.69	5.60	6.50	2.4E-5

Semi-permeable, interlaminate layer #2 (clay and/or silt) is situated between the two compartments. This layer is continuous in the central part of the delta (see map #8) and has a vertical hydraulic conductivity K_v of about 10^{-9} m/sec (see section 5.2.1 of this report).

By applying the general formula:

$$Q_v = K_v * i_v * A$$

where:

Q = annual discharge per square meter (m^3/year/m^2)

K_v = vertical hydraulic conductivity (m/sec) $K_v = 10^{-9}$ m/sec

i_v = vertical hydraulic gradient (m/m or dimensionless)

A = unit surface area of one square meter (m^2)

and using the maximum and minimum values of vertical hydraulic gradient, we obtain the maximum and minimum annual discharges per square meter

i_v	Q_v m^3/an	Remarks
-0.04	-0.0010	Inflow to the upper compartment
0.02	+0.0005	Loss from the upper compartment

These values are very low and reflect the impermeability of semi-permeable layer #2. The aquifer's upper compartment is locally recharged at the rate of 1 liter/year per square meter and locally discharged at the rate of 0.5 liter/year per square meter, depending on the ambient values of the vertical hydraulic gradient (positive in irrigated zones and negative in non-irrigated zones).

In conclusion, we note that the hydraulic pressure difference between the upper and lower compartments is sometimes positive and sometimes negative.

Within the areas influenced by the irrigation zones, the hydraulic pressure in the upper compartment is greater that of the lower compartment. This underlines the impact of irrigation water infiltration on the potentiometric surface and the aquifer's tendency to re-establish the hydrostatic equilibrium.

Outside of these zones the opposite situation prevails. This underlines the importance of evaporation in the areas where this phenomenon is not short-circuited by irrigation.

The areas of seasonal positive vertical hydraulic gradient tend to increase from one year to the next (1987 - 1989). There is also a privileged axis oriented NE-SW, passing through the town of Rosso, and bordering the Lampsar valley. This axis corresponds to the highest density of irrigated perimeters (Lampsar, Grande Digue Tellel Kassak, M'Pourie and a multitude of small irrigated perimeters (PIV)).

Semi-permeable layer #2 is practically totally impermeable.

8 CONCLUSIONS

8.1 Aquifer characteristics

8.1.1 Aquifer definition

The Senegal River delta, a distinct region of the Senegal River Valley, contains a compartmentalized aquifer composed of fine grained sands and silts.

The sediments (sand, silt and clay) of which the compartmentalized aquifer is composed are generally unconsolidated and belong to the Quaternary stratigraphic series: Nouakchottian and Inchirrian deposits of marine origin; Ogolian deposits of eolian origin. These sediments, except for the Ogolian sands, have quite heterogenous vertical and horizontal granulometry.

The aquifer's upper compartment is generally of Nouakchottian sediments. The thickness of this compartment (E_{uc}) varies from 0 to 12 meters. This compartment is spatially discontinuous.

The upper compartment is covered by semi-permeable layer #1 (clay and/or silt) of Recent/Sub-Actual sediments and sometimes of the upper part of the Nouakchottian sediments. Semi-permeable layer #1 has a median thickness ($E_{sp\#1}$) of 2.00 m.

The aquifer's lower compartment is mostly composed of Inchirrian sediments. The thickness of the aquifer's lower compartment (E_{lc}) was not determined by project activities.

This compartment is separated from the aquifer's upper compartment by interlaminate, semi-permeable layer #2 (clay and/or silt), composed of the upper parts of the Inchirian sediments and, sometimes, of the lower parts of the Nouakchottian sediments. Semi-permeable layer #2 has a median thickness ($E_{sp\#2}$) of 3.00 m.

8.1.2 Aquifer extension

Geostatistical analysis (kriging) of the data from the 252 OMVS piezometers indicates that layers #1 and #2 do not extend continuously throughout the entire area of the delta. Discontinuity zones are evident for both layers, particularly on the delta's edges and in the Eastern part of the delta.

The lateral extensions of the aquifer's upper compartment, including semi-permeable layer #1, are limited:

* to the North and South, by the Oualo/Dieri limits which circumscribe the current floodplain of the delta,

* to the West, by the Atlantic seacoast,

* to the East, by the demarcated confines of the delta. These formations extend beyond the delta,

The lateral extensions of the aquifer's lower compartment, including interlaminate, semi-permeable layer #2 are limited:

* to the East, by the geological limits of the Inchirrian, also mapped structurally,

* to the North and South, these formations extend beyond the borders of the maps shown here.

8.2 Hydrogeological characteristics

8.2.1 Structural hydraulic parameters

The horizontal hydraulic conductivities (K_h) of each compartment are, statistically, indistinguishable. Their common average value is $K_{hu}=4.4*10^{-4}$ cm/sec with a standard deviation of +/- $K_{hu}=4.0*10^{-4}$ cm/sec. The hydraulic parameters characteristic of the upper compartment (with $E_{uc}=8$ m) are:

$$* \; T = KE = 3.2*10^{-5} \; m^2/sec$$

$$* \; S = 4*10^{-4}$$

However, coefficients of transmissivity have been measured in some localities which are more than two orders of magnitude larger (10^{-3} m^2/sec), reflecting great heterogeneity in the aquifer.

The aquifer's upper compartment is capped by semi-permeable layer #1. The vertical hydraulic conductivity of this layer ($K_{v\#1}$) is 0.5 mm/day or 5.8 * 10^{-8} m/sec, the literature reports values ranging from 0.5 to 2 mm/day).

The lower compartment is separated from the aquifer's upper compartment by interlaminate, semi-permeable layer #2. The vertical hydraulic conductivity of this layer ($K_{v\#2}$) is 10^{-7} m/sec.

8.2.2 Confined and/or unconfined aquifer

The upper compartment contains a confined or unconfined aquifer depending upon its water level with respect to semi-permeable layer #1

The unconfined aquifer (water table) zones are located on the Southern borders of the delta and near the irrigated perimeter at Thiagar in the East of the delta.

The lower compartment contains a confined aquifer under interlaminate semi-permeable layer #2.

The two aquifer compartments are hydraulically connected to the Senegal River which constitutes a recharge zone with a length of 143 km (from Faidherbe bridge to the junction of the river and the Tahouey canal). This recharge zone is a linear incision into the aquifer with an average depth of 9.9 meters and average width of 360 meters. During the project's observation period (1987 -1989), the water level upstream of Diama Dam varied from -0.26 m ASL to 1.37 m ASL.

8.2.3 Horizontal flow

Near the watercourses, in the zones influenced by these recharge sources, the horizontal hydraulic gradients (i_h) vary as $0 < i_h < 2.2$ m/km.

The calculated maximum influence distance of the surface waters on adjacent aquifers, without considering evaporation losses, is on the order of 2 km from the watercourses. This represents a land area of 330 km^2, or 7.59% of the delta surface. This theoretical influence distance is confirmed by *in-situ* piezometric observations (between 1.0 and 2.0 km). Computer modeling (Filippi) incorporating evaporation effects, suggested an influence distance of 700 to 800 m, a value which seems to us to be quite reasonable.

The horizontal hydraulic exchanges are limited to infiltration through the banks of watercourses and canals. The corresponding estimated inflow to the aquifer is 1.47E+05 m^3/year. This quantity is negligible. Despite the modest contribution of infiltration through watercourse banks to total hydraulic exchanges, this phenomenon is directly related to soil salinization by raising the water table and the thereby increasing capillary flux rates (the evaporation mechanism thus made more efficient, more salts accumulate in the surface soils).

Salinization zones are located near water table recharge areas of which there are two types: watercourses and irrigated perimeters. The increase in irrigated land area and especially the intensification of agricultural cycles (three agricultural seasons are possible) will irremediably cause an increase in the rate of soil salinization, particularly in the zones located between two recharge areas less than 2 km apart (Débi, Boundoum, M'Pourie).

The infiltration of water through the watercourse banks is systematically oriented from the watercourses toward the adjacent aquifers, throughout the hydrologic cycle. This situation will be intensified with the construction of the dike on the right bank at which time the water level in the river will vary from 1.5 m ASL to 2.5 m ASL.

The interstitial flow velocities (V_n) calculated from hydraulic conductivity (Kmin=$K_\mu - K_\sigma$ and Kmax=$K_\mu + K_\sigma$) for a gradient $Dh_{2.0}$ = 2 m (corresponding to the flood period or the water level to be maintained by the dam upon completion of the right bank dike) and for a porosity (n) of 0.15 (value used by the project) are:

$$V_n \text{ (Kmin, } Dh_{2.0}, n=0.15) = 0.04 \text{ m/year}$$
$$V_n \text{ (Kmax, } Dh_{2.0}, n=0.15) = 4.20 \text{ m/year}$$

These interstitial flow velocities are low and signify that very little saline water will be replaced by fresh water.

The impact of Diama Dam on land adjacent to the river will be limited to a corridor 4 km wide (2 km on each side of the river bed). Soils in this band will be very vulnerable to degradation from salts, especially in the proximity of recharge zones related to irrigation. The substitution of saline water by fresh water will not occur.

Apart from the areas adjacent to watercourses, the potentiometric surfaces are constantly negative *outside of the irrigated perimeters* (-0.7 m ASL June '88 and -0.2 m ASL October '88). Inside of the irrigated perimeters they fluctuate between (-0.3 m ASL June 88 and +0.4 m ASL October 88).

The horizontal hydraulic gradients (i_h) are practically null except for in the zones influenced by watercourses and near irrigated perimeters and thus do not induce horizontal groundwater percolation.

8.2.4 Vertical flow

In the absence of significant horizontal flow, it is accepted that the hydraulic exchanges are essentially vertical.

The vertical exchanges are controlled by the *inflows* related to the infiltration of annual precipitation (P=242 mm (1988)) and irrigation water (P_{irr} = 951 mm (rainy season)) and by *losses* related to evaporation from the shallow water table and recharge of the aquifer's upper compartment.

Evaporation from the water table is a function of the water table depth. Theoretically, the capillary rise corresponding to the median water table depth is on the order of 0.3 mm/day.

The median seasonal static water table depths for piezometers located inside and outside of irrigated perimeters varies from 2.06 m (rainy season 1987) to 2.52 m (dry season 1987). A slight rise was measured in 1989.

The seasonal water table fluctuation is about 0.3 m in the non-irrigated zones and about 0.6 to 0.8 m in the irrigated zones, emphasizing the impact of irrigation water infiltration on the water table.

The potentiometric surface is clearly higher in the irrigated zones, particularly in the Eastern part of the delta (Thiagar perimeter and the CSS) which also coincides with an unconfined aquifer zone (water table).

Recharge of the aquifer's lower compartment is negligible.

The estimated inflows (rainfall and irrigation) are 1.29E+08 m^3/year (1988) and the losses (capillary rise and evaporation) are 1.9E+08 m^3/year. This estimation is probably excessive within the confines of the delta.

8.2.5 Geohydrochemistry

The quality of the water is poor within the limits of the delta.

Saline in the central part of the delta (TDS > 10,000 mg/l), the groundwater becomes only brackish at the delta periphery (1000 mg/l < TDS < 10,000 mg/l). These waters have high sodium adsorption ratios (S.A.R.) and high electrical conductivity values.

The central delta zone coincides with the river channel during the Inchirian epoch.

The groundwater is, therefore, generally inappropriate for human consumption, irrigation, and watering of livestock. Some small localities may have higher quality groundwater but they are the exception and are without geographic extension.

The groundwater's salinity seems to vary a great deal over time but this is apparently illogical and unexplained. Previous studies report the same observation. These variations do not change the designation of the groundwater as "poor quality".

8.3 Summary

Theoretically, the aquifer is unique, heterogenous, anisotropic, composed of two compartments: upper and lower. *In practice*, water management problems are related essentially to the aquifer's upper compartment.

The natural hydraulic equilibrium (annual flood/drought cycle) between the surface waters and the groundwater has been altered since 1964.

In 1964, the peripheral dike on the left bank was completed, protecting 61.6 % of the delta surface area (2769.8 km^2).

In 1986, Diama Dam became operational.

The impact of these land development works has been an elimination of natural recharge zones (topographic depressions flooded annually for about 3 months/year) and a multiplication of scattered seasonal recharge zones (irrigated perimeters) where three crops per year become possible with the dual operation of the Diama and Manantali Dams (irrigation 6 to 9 months/year) and the maintenance of the river at levels up to 2.5 m ASL (possible upon completion of the dike on the right bank, expected for 1991).

The effect of these impacts is the raising of the potentiometric surface (water table) in the recharge zones.

All rises in the potentiometric surface, be they caused by horizontal or vertical flows, linear or point recharge zones, are, in function of their intensities, likely to actively contribute to the degradation of soils by salinization.

The only remedy to this situation is the installation of a drainage system adapted to the conditions of the soils in question.

It would be misleading to try to determine drainage schemes based on the statistical data contained in this report which are valid for the entire delta. Drainage systems must be designed specifically for each of the developed zones. This approach would require a different working scale.

This project's contribution to the hydrogeological knowledge of the delta is considerable in that it has created a geostatistical view of the aquifer's structure and has provided chronological information on the evolution of the piezometric fluctuations and the physical-chemical variations.

These basic data, indispensable to developers, will permit the establishment of more realistic development plans.

9 RECOMMENDATIONS

9.1 Short term work program

9.1.1 Continuation of interpretation work - small scale

This synthesis report - volume 2 - deals uniquely with the delta region. This geographic limit was imposed by the June 30, 1990 deadline.

It would, evidently, be desirable to continue the thematic mapping and interpretation of results for the whole valley.

On a small scale, the following geographic sectioning is proposed:

* the lower valley and the lower middle valley, (Z1) located between coordinates MTU-X 426 and MTU-X 580, corresponding approximately to the limit of influence of Diama Dam (elevation 2.5 m ASL),

* the upper middle valley and the upper valley (Z2) located between coordinates MTU-X 580 and MTU-X 818, enclosing the suspected Maestrichtian recharge zone.

Considering the irregular distribution of the OMVS piezometric network, it is possible that the sectioning proposed above be redefined.

For continuation of the interpretation work, OMVS has trained personnel, equipment, computer materials and a working methodology, all in place at the Groundwater Monitoring Unit.

Some of the geological maps for zone (Z1) already exist in the data base. All the basic digitalization work (river and streams, the topography, the piezometry, the locations of irrigated perimeters, towns, raingauges, and water level scales) has been completed for the entire Senegal River Valley, thus covering the Z1 and Z2 regions.

Despite this real progress, much of the data analysis and interpretation remains to be done. Production of this report required an important quantity of work, more than 6 months. Considering that the delta constitutes one of the three regions of the valley (delta, Z1 and Z2), another year of analysis and interpretation will be needed to write a similar report for the entire valley, 6 months per region.

Without the support of technically qualified personnel, the GMU chief, who is also responsible for the data base, will not be able to perform all the technical tasks involved in the production of the reports (the hydrogeological cartography, the exploitation of the GES data base, the data interpretation, etc.). It is necessary to take into consideration the institutional recommendations made in the final report - Volume #1.

9.1.2 Continuation of interpretation work - large scale

The cartographic scale used in this report (approximately 1 cm = 12 km) permits the representation of regional characteristics and the exposition of hydrogeological phenomenon for the entire delta. The precision of the maps, which were developed from hydrogeological observations made with an irregularly spaced piezometric network, is approximate. During geostatistical treatment of the input data, extrapolated values were projected onto regular grid points for automatic plotting of the maps, thus the information represented there tends to be slightly removed from the reality.

With a larger scale (1 cm = 2 or 3 km) and the definition of specific geographic targets, it is possible to develop more precise hydrogeological maps. For an idea of the kinds of maps which it is possible to produce, the reader should refer to the list of maps following the table of contents of this report. Greater cartographic precision is especially possible within the limits of the irrigated perimeters, where the piezometer distribution is practically regular. In fact, the construction criteria were for one piezometer per 100 ha.

Therefore, the geographic sectioning of the delta in three sub-zones is recommended:

* DLT_1 includes the zone near Keur Macène and the perimeter at Debi,

* DLT_2 includes the perimeters at Boundoum, Thiagar and M'Pourie,

* DLT_3 includes the environs of Diama Dam.

Several piezometer lines, transverse to the river, are located in each sub-region.

For each of the delta sub-regions, useful source files (geology, water level, piezometry, etc.) exist, for the entire delta region. These files are necessary for the geostatistical treatment which would permit development of the hydrogeological maps for each of the above-mentioned sub-regions.

Development of the suggested thematic maps for each sub-region would be a fairly simple exercise, based on the simple redefinition of the geographic limits of the maps (MTU-X, MTU-Y), and performed with the SURFER software functions.

The time required to produce the maps for the delta, as recommended here, would be on the order of two to three weeks per region.

9.1.3 Procedural changes for the measurement of electrical conductivity

Within the limits of the delta, electrical conductivity measurements have caused some concern with regard to the degree with which they represent the aquifer conditions. The instruments, which were not always appropriate (measurement scale of 0 to 50,000 µS/cm) and the measurement procedures which were used in the field, together with the extreme volatility of this parameter, as remarked by previous studies, are responsible.

In order to alleviate these problems, the project has purchased and received new instruments (measurement scale 0 to 200,000 µS/cm) which will allow direct measurement of the electrical conductivity values encountered in the delta.

In order to make field measurements of electrical conductivity with more certainty, it is suggested:

1) to give priority to salinity monitoring of the piezometer lines which are transverse to watercourses (L1 to L7, see their locations on map #4) and to the piezometer lines which traverse irrigated perimeters (L8 to L12, see their locations on map #4),

2) to maintain the monthly measurement schedule,

3) to systematically empty the 2½ PVC piezometer tubes with appropriately sized submersible pumps before measuring the salinity,

4) to use the newly purchased conductivity meters with the measurement scales from 0 to 200,000 µS/cm.

The submersible pumps for emptying the piezometers are already available to the project: one per sector office. In the absence of pumps, simple foot valves could be used.

The criteria for stopping pumping should be the stabilization of the electrical conductivity values.

Salinity monitoring will be limited by the time required to operate the pumps and complete the piezometer emptying procedure. It would seem that up to 0.5 hours might be required to make a measurement in this way.

9.2 Medium and long term work program

Work programs are determined by the needs of the technical organizations working in the valley. The GMU is specialized in hydrogeology and, consequently, can only make contributions to current problems within the limits of this science. The scope of subjects researched must be proportional to the available means, and should be limited, as much as possible, to unique, precise topics.

Support from organizations which have already dealt with similar research topics would evidently be desirable and depends on the awareness of technical organizations working in the valley.

The results acquired by the GMU have already been distributed as multiple-copied reports to OMVS headquarters, the OMVS member countries and the OMVS Documentation Center. It seems that report reading is a more fastidious activity than attending meetings and seminars.

It is recommended, therefore, that a calendar of meetings be established with the technical organizations working in the valley (ORSTOM, ISRA, SAED, SONADER, CNRADA, the Universities of Dakar and Nouakchott, etc.) with the following objectives:

1) to distribute information about the GMU, its resources, the data and the results acquired since the beginning of its activities,

2) to encourage these various organizations to make direct use of the raw data, as yet untreated, which is contained in the data base (definition of consultation procedures),

3) to define the program of field work and thematic research (soil salinization, water table rise, river - water table recharge, evaporation) in collaboration with one or more of these organizations.

This program should correspond to field needs and should avoid theoretical research topics.

The reader will find below some recommendations which were developed during the course of the project activities and which may help to orient the information sessions to be held with valley developers.

9.2.1 Soil salinization monitoring (BRGM recommendation)

The phenomenon of soil salinization is in the domain of agronomic science. It occurs in relation to evaporation and evapotranspiration of water from surface sources (irrigation water from developed areas of the valley) and from shallow groundwater which rises due to capillarity. Physical and chemical soil phenomena are also involved.

The quantitative evaluation of this phenomenon could be undertaken with the installation of measurement stations which would be located in function of:

- the geology (geological profiles) and pedology of the areas: these criteria would be established with the organizations concerned with agricultural development (ISRA, SAED, SONADER, etc.),

- the depth of the water table and its annual fluctuations (use of the data base concerning piezometric evolution data)

- the local environment of each site (proximity to water courses, swamps, irrigated zones, etc.), how representative it is of other zones where salinization is likely to occur (agronomic criteria), and its proximity to meteorological stations.

It is suggested that 4 stations be installed, each comprising the same equipment:

- a piezometer of small diameter, full-tubed until the water table,

- a set of tensiometers, installed so as to measure the soil water potential in the non-saturated zones (depths of 0.20 m, 0.40 m, 0.60 m, 1,0 m and every 0.50 m thereafter until the water table is reached).

It would be possible to install these stations at shallow depths in the existing piezometer profile lines perpendicular to the river. The measurement of evapotranspiration losses thus obtained could be used to refine the calculations of the lateral river-aquifer exchanges. Two stations would be installed near the experimental agricultural perimeters.

The stations would be monitored monthly (piezometers, salinity and soil moisture content), necessitating field equipment including a neutron probe, which might cause certain difficulties.

The data thus collected would permit an evaluation, for each period of time, of the water volume evaporated through the soil surface. Bi-weekly monitoring could be required in case of strongly varying equilibrium states.

The calculated flow volumes would later be used to quantify the exchanges between the river and the alluvial aquifer.

9.2.2 Lateral hydraulic exchanges with the Quaternary formations (BRGM proposition)

Operation of the dams will induce changes in the water level of the river, spatially and with time. Lateral exchanges with the alluvial aquifer will be affected by the new conditions.

Begun in 1984 with one profile (BRGM 1984), then continued by EUROCONSUL during restoration of the irrigated perimeter at BOUNDOUM, the quantification of the lateral exchanges will be continued through the analysis of many piezometric profiles which are perpendicular to the river, corresponding to the observation period of the project and beyond.

The increase in irrigated land areas and the intensification of agricultural seasons during the annual cycle will lead to rises of the potentiometric surface by vertical flow, spatially and with time.

The OMVS piezometric network contains 7 profiles which are transverse to the river (L1 to L7) within the limits of the delta and 5 other profiles (L8 to L12) within the irrigated perimeters. Their locations are shown on map #4 of this report.

Analysis of lateral flow was made, in this report, on the basis of the piezometric evolution recorded between June 1987 and December 1989 and on the basis of the geologic contexts and the hydrodynamic parameters.

Similar piezometric behavior was observed for all the sites along the river although differences from one site to another reflect the aquifer's heterogenous character.

It is therefore recommended that one or more models be calibrated with the piezometric evolutions recorded along these profiles and then run in order to predict the lateral and/or horizontal flow which will result upon maintenance of higher river water levels in the future.

Among the uninitiated, the term "model" evokes the notion of simplicity and efficiency. This perception is totally false. Confusion has prevailed in regard to this term since the consultancy by Mr. Bolke, USGS expert.

A mathematical model is a precious tool when applied concretely to a topic of research and when manipulated by a trained team. A structure like the GMU cannot take responsibility for any modeling activity because of its staffing limitations. It is possible, however, that the use of one or more mathematical models would be absolutely pertinent in the effort to find answers to problems which are posed.

It is recommended, therefore, that, as a prerequisite to any modeling activity, a seminar be held with one or more modelling specialists who have experience with the problems in the valley and a solid understanding of the project's resources, in order to:

1) develop an inventory of the different mathematical models which are likely to be of use in solving the problems,

2) estimate the complexity and the difficulties involved in using these models,

3) describe the various work scenarios which are possible in light of human and financial resources available at the time.

4) to choose the most appropriate modeling program.

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