British Journal of Applied Science & Technology
4(23): 3342-3359, 2014

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Hydrogeological Information System Elaboration of Coastal Aquifer AQ-2 of Pointe-Noire, in the South-west of Congo-Brazzaville

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Authors' contributions

This work was carried out in collaboration between all authors. Author GDMN designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript and managed literature searches. Authors RRN, BM, CT, DNT and DN managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Original Research Article

Received 3rd July 2013
Accepted 24th April 2014
Published 18th June 2014

ABSTRACT

The region of Pointe-Noire (south-west of Congo-Brazzaville) located on a coastal sedimentary basin of about 6 000 km^2 is primarily formed by unconsolidated rocks with very little interstice porosity. It is made by a complex multi-aquifers system interconnected. Previous studies have highlighted the lack of data and the need to acquire a better knowledge of the groundwater resource in Pointe Noire. This study intends to represent and schematize the functions of the reservoir and the hydrodynamic behaviour of aquifer AQ-2. A Hydrogeological Information System (HIS) of aquifer AQ-2 is drawn up from historical reconstitution of the piezometric heads data carried out of various series of measurements from boreholes and piezometers .Two hydrological zones related to the topography and/or relief of study zone were identified: a zone of the littoral plain, characterized by protuberances and a strong depth of piezometric surface with hydraulic gradient of 0.03, revealing a flow of significant rate and an average permeability which represents a drainage weaker than the recharge; and a zone of the

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plateaux, characterized by a type of hydrogeologic structure called hydraulic threshold representing a fall of piezometric surface and hydraulic gradient (0.005 and 0.006), which can be explained by variations of flow rate or permeability. This morphology is imposed by two phenomena, the contribution of water of the plateau of Hinda on one hand and on the other hand, the general drainage direction revealed by the presence of the semipermeable facies.

Keywords: Hydrogeology; hydrodynamic; flow; aquifer AQ-2; pointe-noire; GIS; HIS.

1. INTRODUCTION

Many studies [1,2,3,4] underline the lack of data and the need to acquire a better knowledge of the groundwater resource. Some authors [5,6] make the point that it is necessary to know the resource characteristics in order to manage its use adequately (functioning, specific exploitation capacity, quality, vulnerability, etc.). Similarly, Abourida [4] and LeFevre [7] face difficulty to make an optimal management of the resource, including its protection and development at a local scale as well at a regional scale [8], due to lack of knowledge associated with a lack of integration of the available data on groundwater.

It thus appears necessary to map and to classify the hydrodynamic properties of the aquifers, to know their zones of recharge and resurgence, and to establish the priority uses. Some studies [4] also estimate that one should maintain an monitoring network of quality and quantity of groundwater in order to better document its hydrodynamic and hydro chemical functioning.

A regional management of groundwater on the basis of geological formation of aquifer seems difficult presently considering that the specific hydrogeologic data available are seldom sufficient at this scale. There exist few documents of overall interpretation of the data on a local or regional basis (hydrogeological maps). Information on the delineation of the aquiferous geological formations, their exploitation potential, their vulnerability, their recharge surfaces, the quality of the groundwater run outs, the bonds with the receiving mediums (water bodies, rivers, wetlands) are often incomplete or scattered between various public and private organizations.

The area of Pointe-Noire is located on the Atlantic coast of central Africa at the south-western extremity of Congo-Brazzaville and its geographical coordinates lie between the meridian lines 11º30 and 12º East and parallels 4º30 and 5º South (Fig. 1). Its area is approximately about 15,660 ha spread out within a radius of 15 km [9,10]. Pointe-Noire region belongs to the coastal sedimentary basin made up of complex hydrogeologic, including multi-layer and other configurations such as the systems of several water tables communicating with each other. The region of Pointe-Noire is located in sedimentary basin consisting of a hydrogeological complex of plio-quaternary, tertiary and secondary deposits containing five aquifer horizons or water tables (Fig. 2), which can be classified successively in the following way: (i) the shallow aquifer AQ-1 (possibly confined), containing free groundwater, corresponding to the saturated medium with the most permeable layers and draining superficial sands; (ii) the deep aquifer AQ-2 (confined), contains artesian, confined, deep groundwater sometimes spouting out in certain places, corresponding to the most permeable layers of the series of the cirques (quaternary). It consists of heterogeneous silt sands alternating with mudstones levels; (iii) the deep aquifer AQ-3 (confined), contains a confined water table corresponding to the most permeable layers of ferruginous sands, made up sometimes of conglomeratic heterogeneous sands alternating with ferruginous concretions; (iv) the deep aquifer AQ-4 (confined) contains a confined water table, laying between semi-permeable substratum and superstratum, corresponding to the most permeable layers of the series gréso-dolomitiqueof the cretaceous (secondary). It consists of clayey sands and dolomitic aggregates; (v) the potential aquifer AQ-5. This water table, known as potential, corresponds to the unit of the dolomite and the calcite of the series calcareous-dolomitic in which losses of circulation were observed in certain structural test drillings mining.

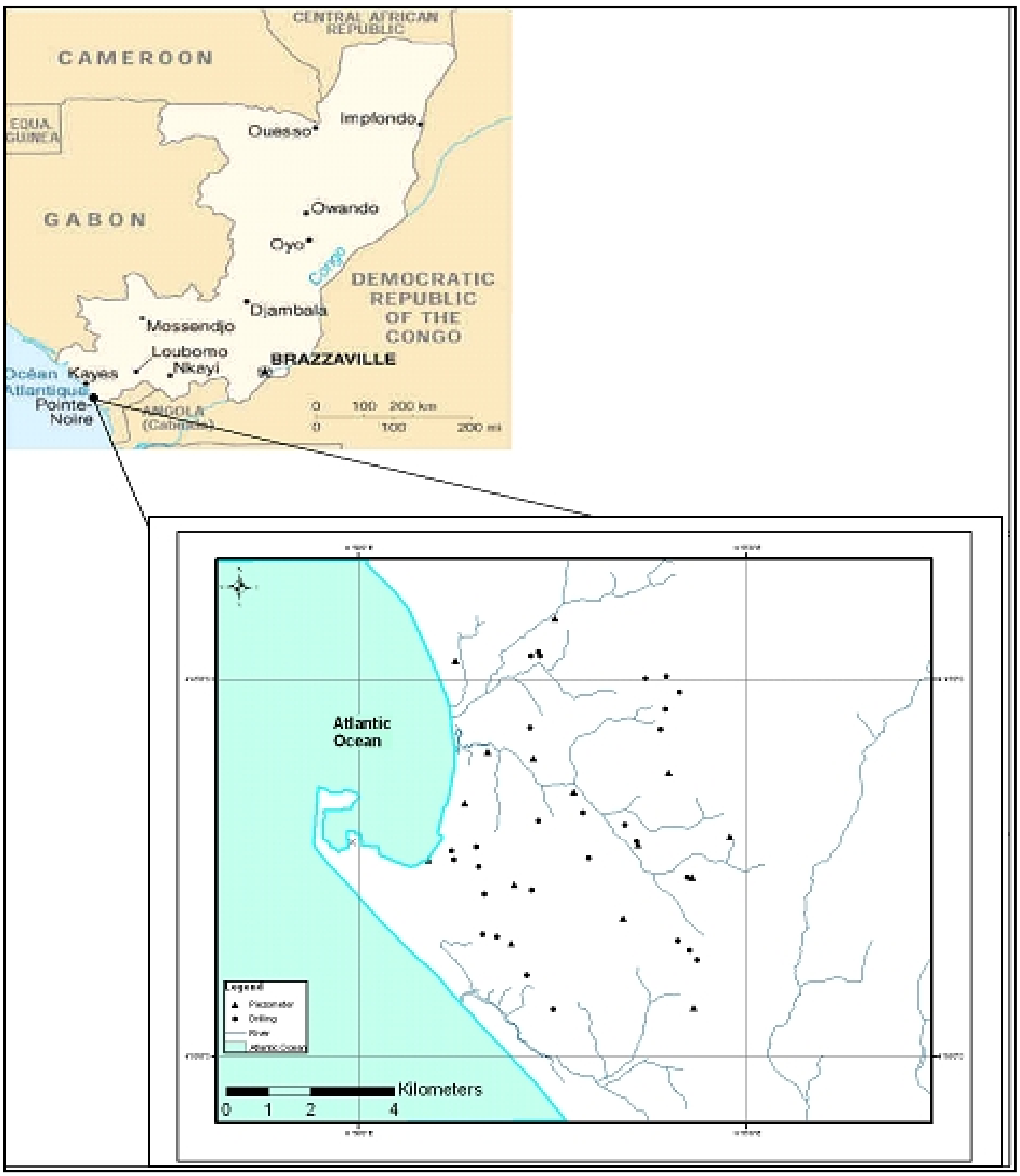

Fig. 1. The study area (Black points indicate the drilling and triangles points indicate the piezometers)

Between the first two higher horizons, some intersected intermediate aquiferous horizons (that we can describe as perched water tables) seem to arise in certain drillings, related to the argillaceous orconglomeratic horizons

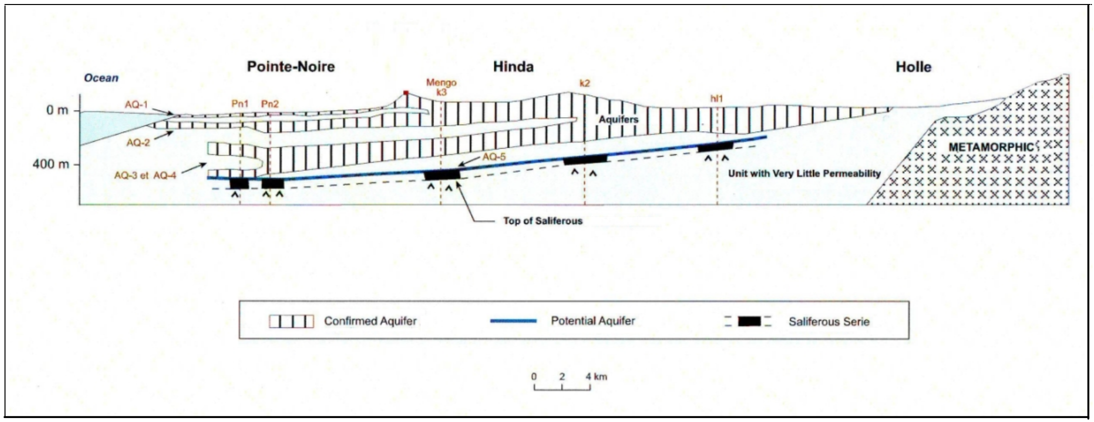

Fig. 2. Hydrogeologic filling of Pointe-Noire (AQ1, AQ2, AQ3, AQ4, AQ5: aquifer layers) [9])

Based on geographical information system (GIS), we establish a retrospective of old [18] and newly acquired data [21] to illustrate the functioning of the aquifer of the region of Pointe-Noire in Republic of Congo. The GIS have considerable advantages, because they enable to synthesize the totality of available information and to facilitate the handling and interpretation of data [8,11,12,13,14]. It is a contribution to the regrouping of useful hydrogeological information for the protection and the conservation of groundwater within a common hydrogeological information system (HIS). The study thus constitutes a precondition to the improvement of information for stock water management in Pointe-Noire, where drinking water exclusively comes from drillings.

2. DATA AND METHODS

On the basis of geologic, digitalized and geo-referenced, hydrodynamic and hydrogeologic data and regional information on the regime of water resources exploitation, we aim to map and classify the hydrodynamic properties of the aquifers for underground water, to know their charging and resurgence areas and to establish their priority uses.

The adopted methodology is to prepare a HIS for the processing of different information that is organized in a database. In relation to the problematic of our work, it appears that one of the fundamental criteria of choice of the best appropriate SIH tool must be the wealth of operations of spatial analysis that it can allow. It must also be able to withstand a relational database.

In a first step, we integrated the data related to all the points of water available in the studied area (coordinates, operating regime, piezometry, hydrodynamic parameters...) so that they could be afterwards imported into Arc View to be combined with the geographical data. The integration of map data collected in the GIS included:

- The digitalization of geometric data (topography, hydrography, geology) with Arc Info;
- The correction of residual errors of digitalization for each layer and the georeferencing of the layers;
- The construction of the topology;
- The assembling of the layers followed by the clipping of each layer according to the limit of the area studied;
- The realization of links between the geometric data and the corresponding attribute tables

This combination makes it possible to do a total analysis.

2.1 Data-gatherings

To carry out the study of the hydrodynamic functionning of the aquifer of Pointe-Noire, the geologic data (coordinate, relief, stratigraphy...), hydrodynamic data (permeability of Darcy, hydraulic transmissivity, coefficient of storage...), and hydrogeologic data (mode of exploitation, piezometry...) are collected (Table 1) for the years 1986 and 2009 (respectively year of beginning of exploitation and year of intensification of exploitation). These collected data are put in the form of DBF files.

2.2 Data Processing

The data processing consists in restoring them in DBF format in order to make them usable in the software (ArcGis). This transformation was carried out in three phases: (i) creation of DBF file; (ii) creation of a cartographic data base (rasters and shaepfiles); (iii) importation of the data by the ArcGis software.

The ArcGis software allows creating the digital maps of Pointe-Noire, drawn from the satellite images and the cartographic data. These digital maps have been superimposed with other digitized informations of various hydrodynamic and hydrologeologic parameters, using the software Surfer 8. This software made it possible to create isovalue maps of various studied parameters. The hydrodynamic, piezometric and chemical data are attributes of the water points stored in DBF files with geographical coordinates. The importation and the establishment of drillings and piezometers with their attributes on the digital maps under Surfer 8 required the transformation of the geographical coordinates of these water points into Lambert coordinates compatible with those of digital maps.

Table 1. Non exhaustive inventory of drillings in the region of pointe-noire

Code	Geographic coordinates		Hydrogeologic data			Hydrodynamic data		
	X	Y	Piezometer (m)		Wall (m)	Permeability of Darcy K ($m.s^{-1}$)	Hydraulic transmissivity T($m^2.s^{-1}$)	Coefficient of storageS(-)
			Z(1986)	Z(2009)				
PZ-1	11°52'31.207"E	4°44'10.533"S	11.5	11.6	119			
PZ-2	11°51'15.357"E	4°44'43.542"S		12.5	102			
PZ-3	11°51'39.236"E	4°45'57.285"S		12.3				
PZ-4	11°52'15.054"E	4°46'10.499"S	10.63	9.5	115			
PZ-6	11°53'58.997"E	4°46'12.736"S	12.75	13.3				
PZ-7	11°51'20.975"E	4°46'37.317"S		6.7				
PZ-8	11°52'45.956"E	4°46'28.187"S		11.6				
PZ-9	11°54'47.457"E	4°47'40.006"S		10.9				
PZ-10	11°54'18,662"E	4°47'37,015"S	14.75	14.5				
PZ-11	11°50'52.883"E	4°47'23.671"S	1.6	2.7				
PZ-12	11°52'0.305"E	4°47'41.931"S	6.55	6.9				
PZ-13	11°53'23.881"E	4°48'8.619"S	3.95	3.6				
PZ-14	11°51'57.496"E	4°48'28.986"S	8.3	6.7				
PZ-15	11°54'19.365"E	4°49'20.256"S		7.4				
F1	11°52'57.193"E	4°47'21.564"S			129.1	$23.17.10^{-5}$	$6.95.10^{-3}$	
F2	11°51'11.143"E	4°47'15.243"S		-11.6	121.5	$19.83.10^{-5}$	$5.95.10^{-3}$	$6.13.10^{-4}$
F3	11°51'13.25"E	4°47'22.266"S		11.0	121.5			
F5	11°51'35.022"E	4°48'22.666"S		6.7	150	$15.33.10^{-5}$	$4.6.10^{-3}$	$5.1.10^{-4}$
F6	11°51'46.259"E	4°48'23.368"S		-5.4	150	$6.33.10^{-4}$	$9.5.10^{-3}$	$4.5.10^{-4}$
F7	11°52'52.979"E	4°46'45.745"S		-18.9	115.1	$26.17.10^{-5}$	$7.85.10^{-3}$	
F8	11°52'19.97"E	4°44'40.432"S		9.8	118	$18.33.10^{-5}$	$3.95.10^{-3}$	$4.2.10^{-5}$
F9	11°52'18.566"E	4°44'37.221"S		-19.7	121.7	$13.00.10^{-5}$	$1.95.10^{-3}$	
F10	11°52'12.947"E	4°44'40.03"S		4.1	116	$24.50.10^{-5}$	4.10^{-3}	$1.5.10^{-4}$
F11	11°54'6.021"E	4°48'26.879"S		-8.9	131	$9.33.10^{-5}$	$1.4.10^{-3}$	
F12	11°54'15,853"E	4°48'33,903"S		11.1	131	$25.66.10^{-5}$	$3.85.10^{-3}$	$1.5.10^{-4}$
F13	11°54'21.472"E	4°48'42.33"S		-6.1	125	$3.66.10^{-5}$	$5.5.10^{-3}$	$1.7.10^{-4}$
F14	11°53'25.286"E	4°46'54.173"S		-24.3	175	$3.83.10^{-5}$	$1.15.10^{-3}$	
F15	11°53'34.416"E	4°47'7.517"S		13.6	168			
F16	11°53'52.677"E	4°45'39.025"S		-19.6				

Table 1 Continued…….

F17	11°52'30.505"E	4°49'22.363"S	-36.5	
F19	11°51'30.105"E	4°47'12.434"S	10.7	
F20	11°52'13.649"E	4°47'46.145"S	-43.3	181.6
F21	11°54'14.448"E	4°47'36.312"S	-51.0	156
F22	11°53'42.142"E	4°44'58.29"S	19.0	132
F23	11°53'57.593"E	4°44'56.183"S	3.8	167
JIKA	11°52'9.435"E	4°48'53.568"S	40.9	
BOPLAC	11°51'36.426"E	4°47'49.656"S	-12.5	41
Sicé	11°51'32.915"E	4°47'28.587"S	-10	44
Loan	11°52'12.947"E	4°45'36.918"S	-27	45
Trabec	11°53'57.593"E	4°45'22.872"S	-11	70
Nana	11°54'7.425"E	4°45'9.527"S	26	74
PNR	11°52'18.566E	4°46'51.364"S	-24.1	44

3. RESULTS AND DISCUSSION

3.1 Geomorphologic Data

The geologic map of the region of Pointe-Noire is derived from satellite pictures taken from Google Earth and georeferenced using ArcGis. This map is superimposed on the digital elevation model (DEM) with a mesh of 100 *m*. DEM represents relief (X, Y, Z (altitude)), by giving to each point of a mesh the altitude of a corresponding point on the ground. This allows to make hypsometric representations (colouring according to the altitude layer (Fig. 3).

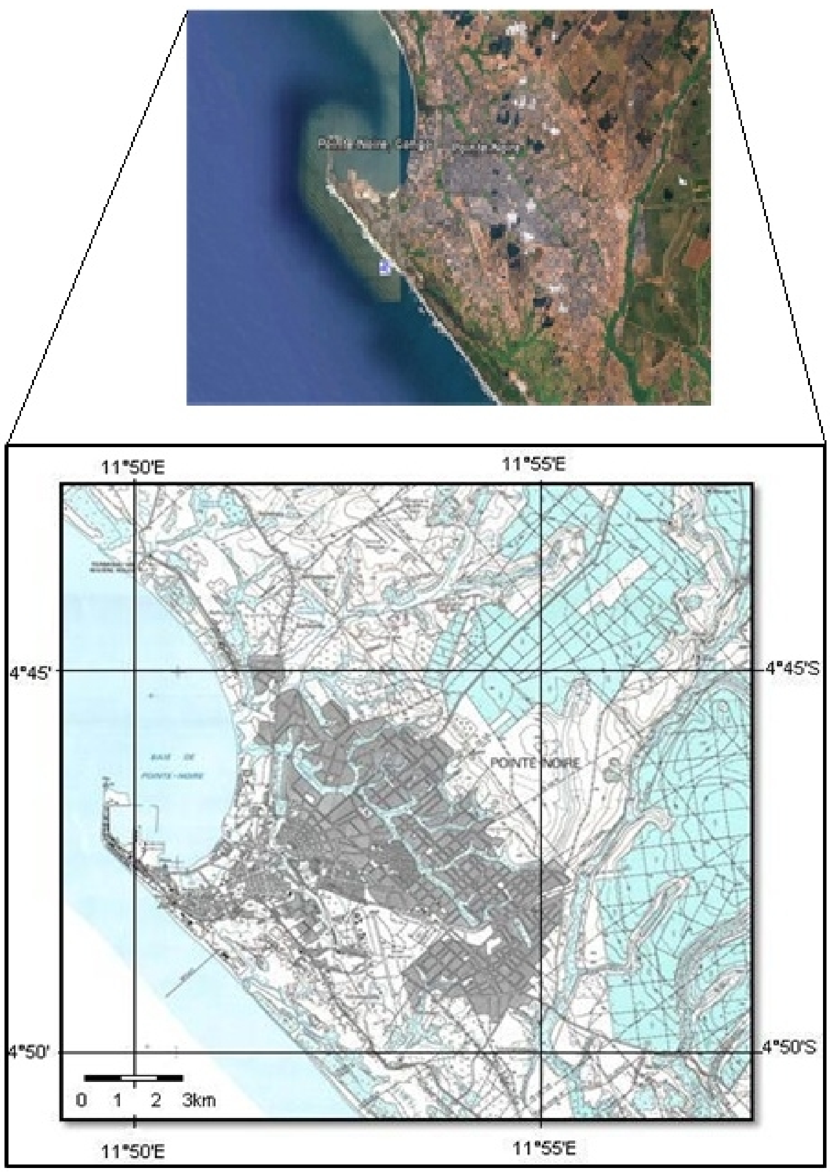

Fig. 3. Topography of the agglomeration in pointe-noire (level curves)

3.2 Hydrodynamic Data

The available data on the hydrodynamic properties, for the region of Pointe-Noire, are drawn from the various pumping tests carried out by SNC-Lavalin, [15]. These various data were used by various authors [14,16,17] and do not seem to have been updated, considering the new drillings of exploitation built at Pointe-Noire.The comparison between the various available data presents certain differences. Indeed, these properties represent indicators which, taking into account the strong exploitation of groundwater at Pointe-Noire, should be the subject of a revaluation and updated including the new data and pumping tests. These various data are superimposed on the digital maps. Each property is connected to a data table from which relevant isovalues can be plotted, such as the Darcy permeability coefficients, the transmissivity and the storage coefficient.

3.2.1 Data of darcy permeability coefficients

We overlaid the permeability coefficients on the digital map drawn from the satellite picture. These updated data were connected to a table under DBF format. The permeability coefficients isovalues map is plotted in Fig. 4.

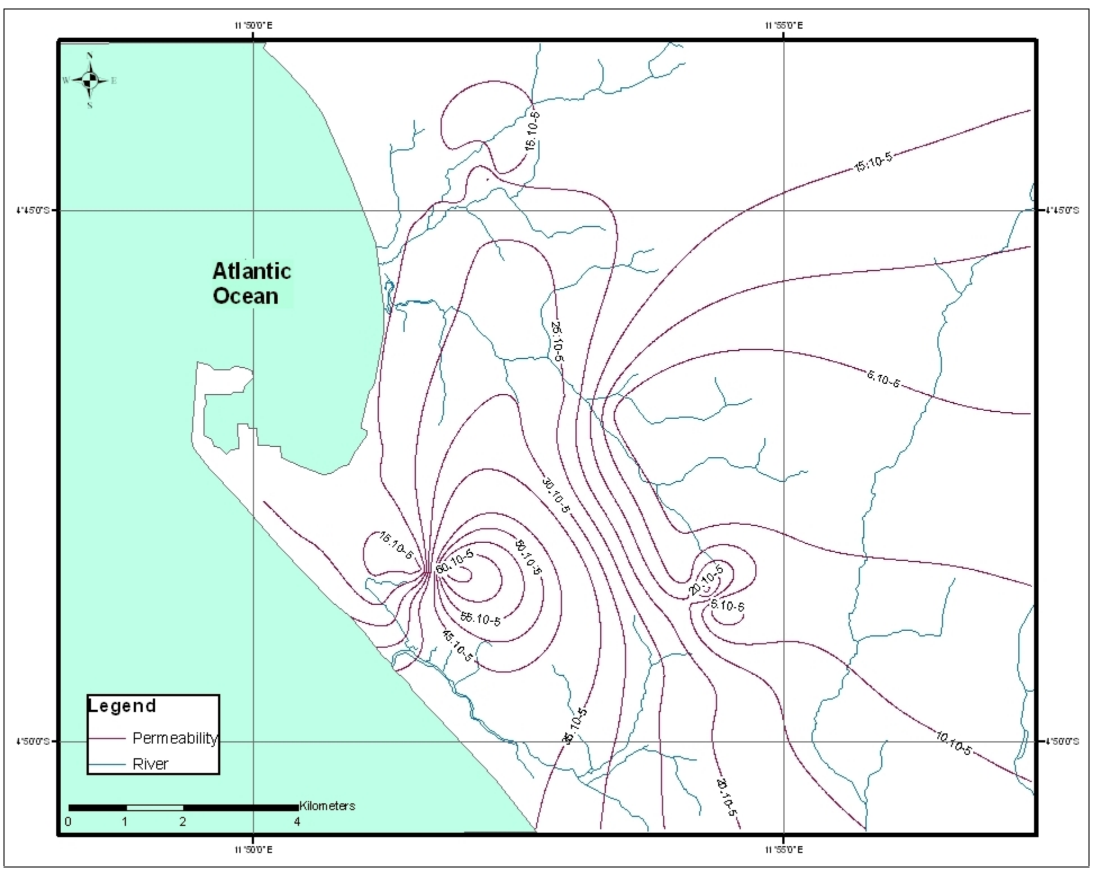

Fig. 4. Darcy permeability in the region of pointe-noire (permeability curves)

3.2.2 Transmissivity data

The aquifer in Pointe-Noireshows a large variability of transmissivity related to the lithologic and geometric heterogeneity of its layers. Various pumping tests carried out previously, [16] allowed the determination of the intervals of variations of the transmissivity. The transmissivity in this region is in the intervals, 8.0×10^{-4} and 9.9×10^{-3} which confirms the good hydrogeological characteristics of the aquifer [21]. The map shows the existence of a zone of high transmissivity taking the shape of an overall East-West oriented channel, beginning in the East towards the centre and finishing next to the ocean coast (Fig. 5). A zone with weak transmissivity also appears next to the zone of good transmissivity, forming a vast depression which is inserted between the east and west zones of good transmissivity.

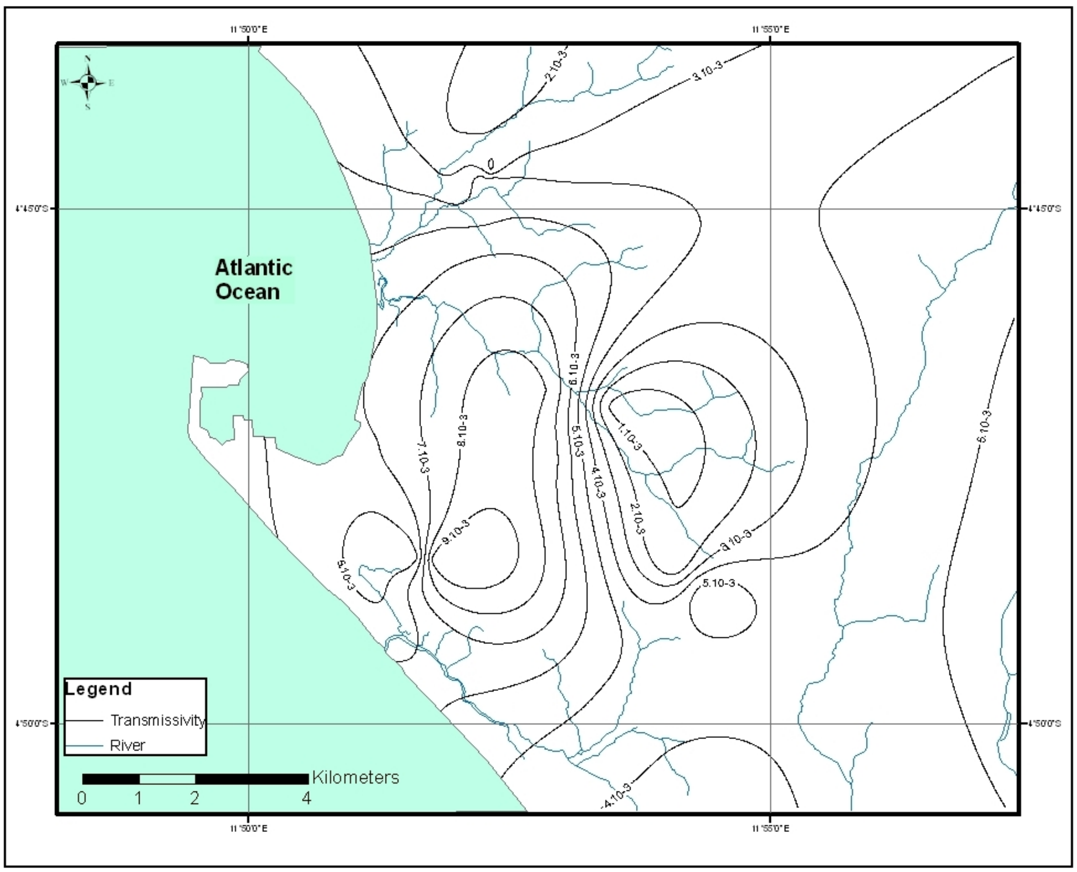

Fig. 5. Transmissivity (transmissivity curves)

3.2.3 Storage coefficient data

Fig. 6, thus, makes it possible to moderate roughly the results relating to the values of transmissivity. The values are all very weak (on average around 10^{-4}) highlighting the captive character of the aquifer of the sedimentary basin in the region of Pointe-Noire. Pessimistic as they are concerning the capacity of production, but also the capacity of "ingestion" of the aquiferous system, these results must however be moderated by the existence of large flow drillings when the need is felt somewhere.

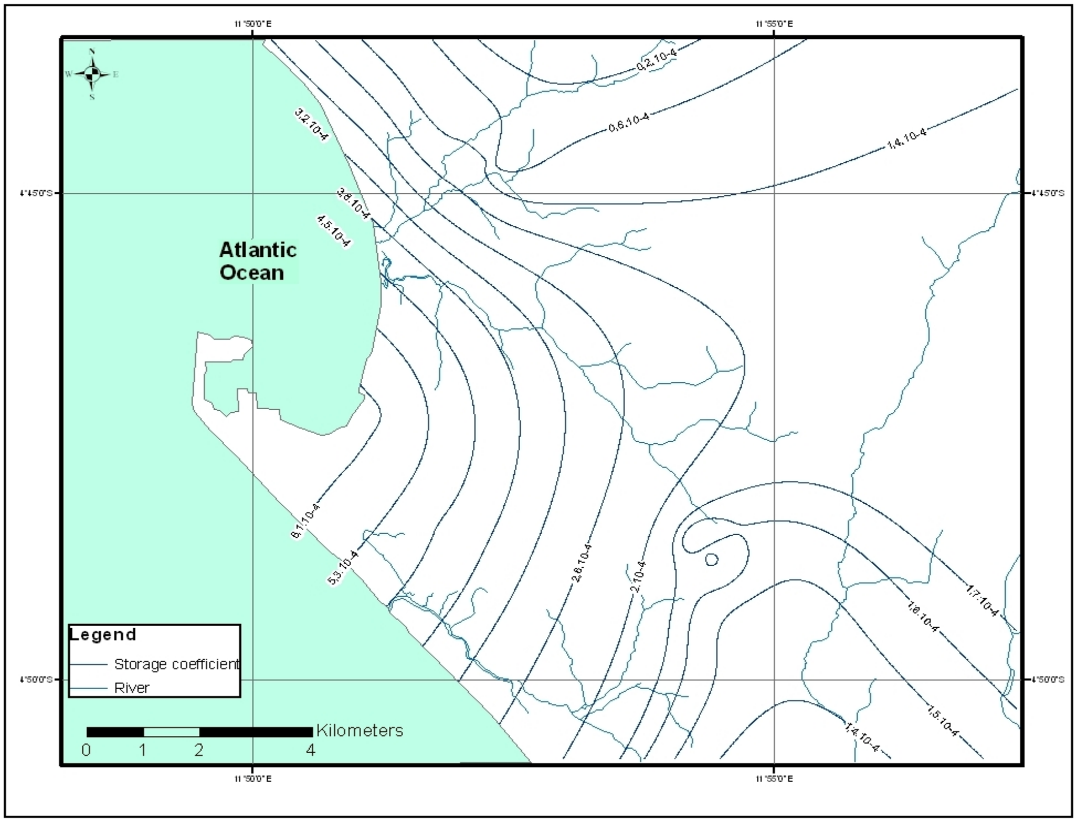

Fig. 6. Storage coefficients

3.3 Hydrogeologic Data

3.3.1 Aquiferwall data

The map of the aquifer wall (Fig. 7) was obtained from the interpolation of the depth values of the AQ-2 contained in the various drilling presentation map, by the software ArcGis. Then, we exported contours in shape file form in the GIS. The map informs us about the thickness variations of the circus series and their analysis makes it possible to deduce several structures from them: the concentric structure of the curves in the littoral fringe could be related to the filling of the basin by the plio-pleistocenic deposits. In the Hinda plateau, there is a depression marked by the increase thickness of the plio-pleistocenic deposits. This structure could be elated to the cliff parallel to the coast.

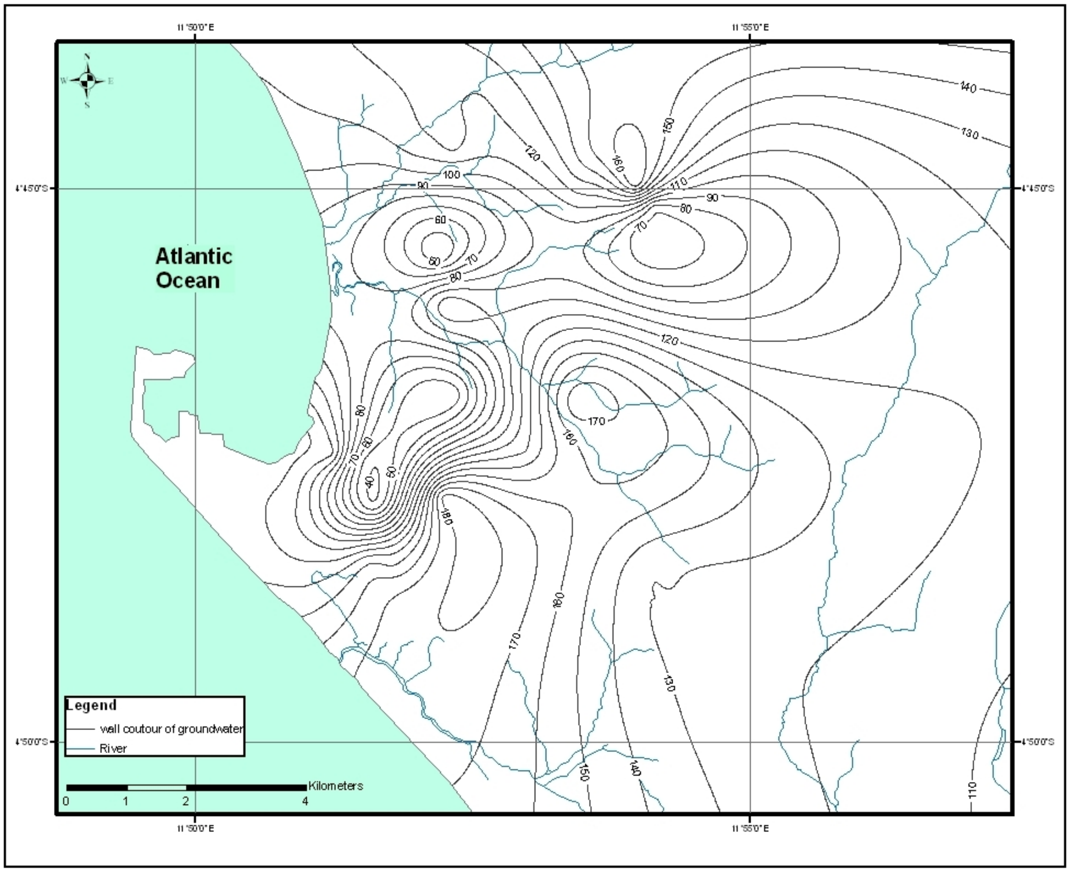

Fig. 7. Map of AQ-2 wall depth

3.3.2 Piezometric data

The temporal variation of the piezometric level of the water table of the AQ-2 was measured in a discontinuous way since 1986. We carried out the largest series of measurement in this region (two months: from July to August 2009). The level of water in the piezometers covering the entire region was measured with the electric probe compared with the surface of the ground. Measurements obtained during this series were added to some measurements coming from data of former studies [17,18]). The Fig. 8 illustrates the various points of measurement of water table AQ-2.Knowing the topographic height of each piezometer, we have deduced the piezometric head of all the points of measurement and we carried out the morphological analysis of piezometric surface in time and space.

3.3.3 Space-time piezometric evolution

The study of the cartography of the aquifer makes it possible to consider the piezometric surface of the aquifer in Pointe-Noire. This map has a specific morphology comparable to that of a topographic surface: depression, undulation, ruptures of the slopes, accidents, etc. This work allows to represent the configuration, the structure and to schematize the functions of the reservoir and the hydrodynamic behaviour of the aquifer. This allows to define at first approximation the aquiferous system according to the geological conditions and to have a first estimate of its mode of supply and its flow direction [19,20,21]. The approach is based on the historical reconstitution of the piezometric heads of drillings and piezometers of various series of measurements in the region of Pointe-Noire. Thus, in order to make a description of aquifer AQ-2, the depths and rises in the static and dynamic levels of groundwater were measured. The static level corresponds to the measurements taken in non-exploited piezometric drillings and makes it possible to emphasize the directions of flows. The dynamic level corresponds to measures taken in exploitation drillings and makes it possible to emphasize the impact of the exploitation of drillings. It should be noted that piezometry is presented only as an indication considering various dates of measurements, the low number of wells of observation at certain places and the possibility that certain drillings collect water in aquifer AQ-3.

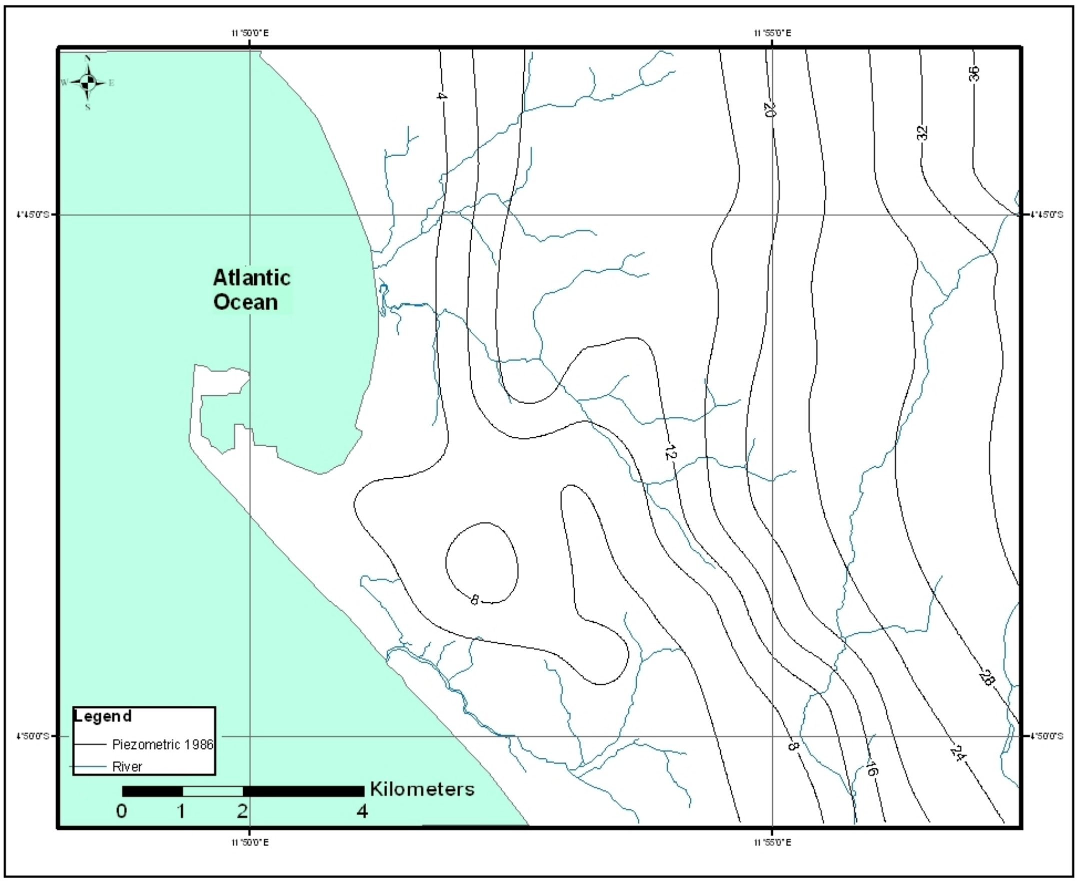

Fig. 8. Piezometric Map in 1986

The piezometric maps illustrated on Figs. 8 and 9 plotted by using the data of 1986 and the average of all the data gathered in 2009 collected in drillings and piezometers, presents a synthesis of the hydrogeologic study, and schematizes the pipe function of the reservoir and the hydrodynamic behaviour of the AQ-2, taking limit conditions into. The map represents the spatial distribution of the piezometric heads and the average hydraulic potentials of the AQ-2.

The layout of the regional piezometric map makes it possible to highlight and to allot limits of hydraulic nature to an aquiferous system. Here, we represent the maps of the piezometry observed in 1986 (year under review before the intensification of the exploitation of the water table in the agglomeration), and 2009 (one of the years of the period of overexploitation) of water table AQ-2.

The piezometric map of 1986 (Fig. 8) presents an almost homogeneous hydrogeologic unit, characterized by a general flow of the east towards the west. In the region of Pointe-Noire, piezometric evolution presents small variations (between 0.1 and 3 m/year). These can be increasing or decreasing variations according to the period and the piezometer (Table 1).

The piezometric map (Fig. 9) obtained by using the data collected in 2009 in drillings and piezometers, presents an executive summary of the hydrogeological study, and schematizes the funnel function of the tank and the hydrodynamic behavior of the AQ-2 (with boundary conditions). It represents the spatial distribution of the loads and potential hydraulics of the AQ-2.

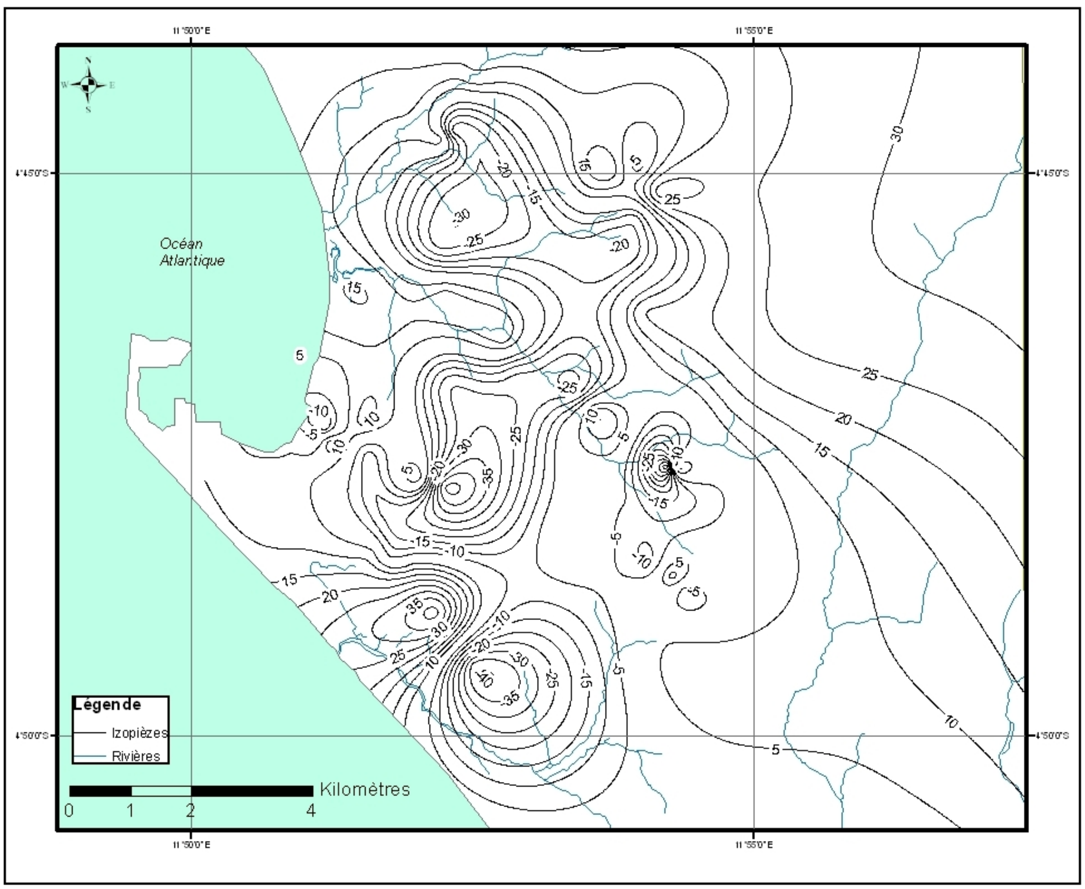

Fig. 9. Piezometric Map in 2009

The shape of the piezometric curves offers good indicators for the identification of the entry zones and the axes of flow. Among the latter, one can generally identify East / West and North-East / South-West.

The main entry surfaces of the water table, seem to be primarily made up by the East outcrops of the Hinda plateau (contour line 25 m and 30 m), which easily explains a setting of charges oriented towards the east.

The morphological analysis of this map allows identifying two hydrological zones related to the topography and/or the relief of the zone of study: a zone of the littoral plain characterized by closed curves and a zone of plateau characterized by curves parallel with the slope. The zone of the littoral fringe presents closed curves which express protuberances and a strong depth of piezometric surface. The hydraulic gradient of 0.03 is the expression of a significant flow and an average permeability which represents weaker drainage than supply. This hydrogeological structure indicates two types of water tables: A water table with divergent nets in the North and a water table with convergent nets in the South representing an overexploitation. The zone of the plateau presents clearly different characteristics: the relief is accentuated and increases as one moves away from the ocean. The piezometric curves are roughly parallel to the slope and the oceanic coast show the presence of a water table with divergent nets. This piezometric surface expresses a type of hydrogeological structure called hydraulic threshold, representing a fall of piezometric surface and hydraulic gradient (0,005 and 0,006) which can be explained by variations of flow or permeability. This zone presents also a cone of depression towards the north characterized by the existence of the curved lines.

Aquifer AQ-2 has an elementary structure which does not translate its morphology. This is the result of either a strong flow, or a low coefficient of permeability, or the convergence of these two characters. This morphology is imposed by two phenomena, on the one hand the contribution of water of the Hinda plateau and on the other hand, the axial general drainage underlined by the presence of the semipermeable facades. The groundwater reserve W is evaluated by the treatment of a couple of data: volume v of the section of the considered aquifer (saturated reservoir); and the coefficient of storage of the aquifers with confined water table S. The calculation of the volume of the section of the considered aquifer is based on the planimetric interpretation of the maps in isopachs curves, the draft at saturation of the aquifer as the average thickness. The volume to be considered in the case of a confined water table will be thus, the product of average thickness collected by the section of the domain. We present here, a coarse estimate of the reserve because of the area dimension (surface of Pointe-Noire) which is so large that the hydrodynamic data proved to be insufficient. By considering a surface of 15660 hectares with a thickness of 30 m and an average hydraulic gradient calculated in all the region of 0.02, we estimated the groundwater reserve of the water table of deep sands as follows [21]:

$$W = 30m \times 15660 \times 10^4 m^2 \times 2 \times 10^{-2} = 94743000 m^3$$

The obtained volume represents the water capacity of considered region. It is higher than the annual extractions of water estimated in the locality (2 476 489 m^3 for about fifteen drillings).

4. CONCLUSION

In the region of Pointe-Noire the different aquifers are well individualized, but the most productive and more exploited remains that of the AQ-2 although it has zones of variable productivity. The AQ-2 is a largely exploited aquifer which frequently combines the hydrodynamic characteristics of a sedimentary medium with strong velocity of transfer. This material, with a high total porosity of about 20% and an average transmissivity of $8\times10^{-3} m^2.s^{-1}$ [12], constitutes a complex aquifer with a matrix porosity, enabling it to store a significant quantity of water. The confined water table of our zone of study has coefficients of storage of 4.2×10^{-5} to 5.1×10^{-4}. In the region of Pointe-Noire, aquifer AQ-2 is in a captive mode sometimes spouting out in certain places. It is essentially supplied with rainwater in all the domain of the upper reach outcrops. It is drained upstream by the network of river to which it brings its exceptionally regular flow. It is not very porous and not very permeable. Consequently, the storage and the gravity transfer of water are only possible thanks to the existence of the zones of drainage, sufficiently dense and inter-connected with other exploitable aquifers. However, in a region where these conditions are not met, the aquifers have very strong variations of productivity as water is not able to circulate within the blocks limited by the compartments.

The GIS have considerable advantages, because they are at the same time able to memorize the totality of available information and to facilitate the handling and the interpretation of the data. It is a contribution to the regrouping of useful hydrogeological information for the protection and the conservation of groundwater within the same hydrogeological information system (HIS). The study thus constitutes a precondition to the improvement of information of stock management water in Pointe-Noire where consumption water exclusively comes from drillings.

ACKNOWLEDGEMENTS

We would like to thank Professors Benjamin Evayoulou Banga Mboko and Remi D'Annunzio for their remarks and observations, the National Company of Water Supply (SNDE) of Congo Brazzaville for its technical support and International Foundation for Science for his financial support of Moukandi Nkaya Thesis under research grants awarded 2008.

COMPETING INTERESTS

Authors have declared that there are no competing interests.

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