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MODELING OF GROUNDWATER FLOW AND DRAWDOWN EVOLUTION SIMULATION OF ABIDJAN AQUIFER (CÔTE D'IVOIRE)

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ABSTRACT

Groundwater is the main source of drinking water supply to Abidjan District. However, the rapid growth of Abidjan population and the highest demand in water are a threat quantitative of this resource. This study has been undertaken by means to obtain the order of drawdown magnitude of Abidjan aquifer on the horizon from 2005 to 2030 according to an increasing in flow rates of pumping stations provided by SODECI to satisfy the highest demand in drinking water. To achieve such an objective, a hydrogeological model of Abidjan aquifer has been designed using the code

MODFLOW by using historical data (geological, hydrogeological and piezometric) to predict the impact such an exploitation on this aquifer. The numerical model designed was calibrated in steady-state mode with piezometric data from 1978 and then validated in transient mode from piezometric data from 1992. The piezometry evolution simulation and the drawdown calculation from 2005 to 2030 were made in transient mode. The results of this model revealed that the project of rates increase from 2005 to 2030 is possible. These flows will pass from 256 490 m^3/day to 310 760 m^3/day. However, the highest drawdowns will be observed into piezometers; Anonkoua kouté 2 (15.71 m), Niangon 1 (6.86 m) and Adonkoua (6.24 m).

Keywords: Modeling, Groundwater, Piezometry, Drawdown, MODFLOW, Abidjan aquifer

INTRODUCTION

Water supply of the Abidjan population is assured only by the groundwater contained in the sandy formations in the region. The sustainability of Abidjan District groundwater quality is threatened because of the insufficient or non-functioning of the sewage treatment plants and installation of the anarchic of some potentially polluting activities (Kouamé *et al.*, 2008; Koffi *et al.*, 2012). The phenomenon of increase in the consumption of groundwater is caused partly by war, which resulted in a rapid and massive displacement of populations towards Abidjan. This displacement of the population exerts an enormous pressure on Abidjan groundwater resources (Jourda *et al.*, 2006). Abidjan district, located in the south of Côte d'Ivoire, is a recent creation legal status of Côte d'Ivoire (Figure 1). It has an urbanization rate of 95.8% and account four urban cores:

• the main core is Abidjan city, which represents the economic capital of Côte d'Ivoire;

• the communities of Anyama (in the North), Bingerville (in the East) and Songon (in the West) are the three other urban cores of Abidjan district.

With an area of 2 119 km^2, Abidjan district comprises an estimated population of 3 125 890 in 1998 (INS, 2001). This population has increased today to reach 5 million in 2006 due to the socio-political crisis in the country since September 2002 (MPD, 2006). To supply water this population, annual production of Water Distributive of Côte d'Ivoire Society (SODECI) increased from 7 million m^3 in 1993 to 12 million m^3 in 2002 (Kouamé *et al.*, 2009). Abidjan district groundwater is contained in the coastal sedimentary basin of Cretaceous to Quaternary age (Aghui and Biémi, 1984). This basin presents enormous potential in groundwater. These groundwater resources are formed by three levels aquifers and only the Continental Terminal aquifer called locally "Abidjan aquifer" is exploited for the drinking water supply by SODECI (Figure 2). This study was therefore undertaken to predict the evolution of Abidjan aquifer level to 2005 from 2030 according to a scenario of increase in water production stations provided by SODECI to face of high demand in drinking water. It also aims to determine the convenient zones to the establishment of new wells in a concern of reduction of the Abidjan aquifer drawdown to avoid any probability of groundwater contamination by saline intrusion. This requires the development of a mathematical model to predict the impact of such an operation on Abidjan aquifer.

MATERIAL AND METHOD

Material

The approach used in the framework of this study has requires the establishment of a database. The initial data used result from geological and hydrogeological works carried out on Abidjan aquifer by several authors (Guérin, 1962; Loroux, 1978; Tastet, 1979; Jourda, 1987; SOGREAH, 1992; SOGREAH., 1996). From a synthesis of these works, hydrodynamic parameters such as hydraulic conductivity (permeability), coefficient of storing and porosity of two sand layers (coarse sand and fine sands) have been retained.

Piezometric data of 1978, 1992 and 2001 outcomes from the work of SOGREAH (1992), Oga (1998), SODECI. (2001) and Sombo (2006) have been used in the realization of this model. The flows of these various stations have also been included in this model. It was collected in the work of HYDROEXPERT (2001) and from the SODECI. Finally, topographic map and bedrock topography were also used in this modeling. The bedrock topography has been carried out by the Company General of Geophysics (CGG) in 1977 and 1981-1982 (Aghui and Biémi, 1984). Softwares, such as MODFLOW 3.0, ArcView 3.2 and MapInfo 7.5 were used for the treatment of all these data.

Methodological Approach

Modeling is a digital schematization of the hydrogeological system. It allows you to pass to a natural complex system, the ground, to a whole digital, the model. Consequently, it’s a question of two very different realities (Leduc, 2005). The digital model development requires several steps (Leblanc, 1999) such as the determination of objectives to be achieved, the choice of the software used, the design of conceptual models and digital, model calibration and verification, the realization of predictive simulations and finally the critical analysis of the results obtained (Figure 3).

Objective

This model aims to simulate the evolution of Abidjan groundwater level face to the gradual increasing of the pumping proposed by the SODECI to satisfy the high demand in water. The simulations will be made in transient regime over a period of 52 years in taking the year 1978 as reference year (beginning of Abidjan aquifer exploitation).

Software Used

The numerical model was developed using MODFLOW, a widely used code, developed by the United States Geological Survey (USGS) through the commercial software Visual MODFLOW version 3.0.0 provided by Waterloo Hydrogeologic (Mac Donald and Harbaugh, 1988). This software integrates three codes:

• MODFLOW for the groundwater flow simulation;

• ModPath simulates the pathways of water particles;

• MT3D for mass transfer simulation.

The mathematical digital models of hydrodynamics flow are based on finite difference or finite element code. MODFLOW allows approaching flow equation solution through finite-difference method (Sahbi *et al.*, 2005).

Hydrogeological Model

Abidjan aquifer is free on the whole of the sedimentary basin and based on birrimians schists which constitutes the impervious base (Tastet, 1979; SOGREAH., 1996). The top of Abidjan aquifer is constituted by the topography which varies from 0 to 100 m in elevation. The bottom of the aquifer is located at the contact of fine sands with the granitic bedrock whose elevations varies between +30 and -150 m according bedrock topography map (Aghui and Biémi, 1984). The thickness of the aquifer varies between 20 m in the North and 160 m in the south (Jourda, 1987). The model is double-layered with the higher layer representing coarse sand and the lower layer of fine sand (SOGREAH., 1996). The bottom of map being used as reference for the model is obtained by digitalization of the topographic map to 1/50 000e of 1974 (IGCI, 1974) under the environment of MapInfo. For the space discretization (grid) of the model, square cell 1 km x 1 km size were used on the study zone (Kouamé *et al.*, 2008). The size of the grid was then refined to 250 m x 250 m size around well fields in exploitation. In order to better represent the limits of the area to be modeled, the cells which did not belong to the aquifer, were inactivated. Thus the model is made of 20 564 cells distributed in 194 columns and 106 lines (Figure 4).

Boundary Conditions

The boundary conditions of the model are constituted of "constant head", "river" and "recharge" type (Figure 5). The head assigned in boundary conditions of constant head and river corresponds to the rise in the rivers represented, while the conductance of the river boundary type was determined by trial and error. The value of constant head assigned in North is 60 m and 0.2 m in South of the model. The boundary condition of recharge type is assigned uniformly on the whole of the first layer of the model and corresponds to 247.4 mm/year. This value has been obtained from precipitation data from 1963 to 2000 with EVC program (Kouamé *et al.*, 2009).

Model Calibration and Verification

Model calibration aims to reproduce to the best the hydrodynamics operation in the whole of Abidjan aquifer by adjusting various parameters that can be vary while remaining in the range of realistic values (Leduc, 2005).

In order to facilitate the adjustment of parameters, model calibration is made in two times: in steady-state and transient regimes. In this study, the calibration is done "manual" or "groping" way because of insufficiency of piezometries data. This type of calibration follows this process:

- adjustment of hydrodynamic parameters;
- simulation of the model;
- comparison of calculated heads *versus* heads measured (if differences are large then we retry operations again).

These operations are executed until they get low error of calibration thus reflecting a good calibration between heads "observed" on the ground and those "calculated" by the model (Anderson and Woessner, 1992; Gurwin and Lubezynski., 2004). The Normalized Root Mean Squared residual or NRMS, expressed as a percentage, is the representative parameter of the model and must be less than 10% for an adequate calibration (Leblanc, 1999). The model can be used as simulations, if it is valid. For this study, 1992 piezometric data have been simulated in transient regime from those of 1978. A comparison between simulated and observed heads in 1992 has been carried out. This comparison will help validate the model

Predictive Simulations

Initial Piezometry Simulation

The reconstitution of the initial piezometry (year 1960) of Abidjan aquifer has been carried out from 46 piezometric data of 1978 collected in SOGREAH (1992) and Sombo (2006) Works. It was conducted in steady-state mode. In fact, 1960-1978 periods has been regarded as a period during which a few wells were in operation (Table 1). As well, the hypothesis that the pumping rates in 1978 are in balance with the recharge of the Abidjan aquifer, has been issued. Piezometric data in 1978 are therefore considered not influenced by executed withdrawals.

Piezometry Simulation in 2005

The representation of the piezometry in 2005 has been made in transient mode to helping of the pumping rates updated with collected data from SODECI. They are assigned to a cell representing the whole of the drilling in operation at well field.

Prediction of Piezometry Evolution

These simulations have been carried out in transient mode over 52 years in taking 1978 as reference year (beginning of Abidjan aquifer exploitation). The piezometric data in 1992 were used to validate the model in transient mode in order to its use for simulations of piezometry evolution from 1992 to 2030. The pumping rates used in the model for the period modeled were divided into 7 periods of constant flow for the transient arrangements (Table 2). The projections for 2005 to 2030 correspond to the estimates made by SODECI. The difference between reference piezometries and predictive piezometries into differents piezometers of the model will determine the drawdown cone caused by the increasing of pumping rates.

RESULTS AND DISCUSSION

Model Calibration and Verification

The calibration has been verified using parameters provided by the software. This is observed *versus* calculated heads graph and statistics related to this graph.

Steady-State Mode

The calibration in steady-state mode has carried out manually and has allowed obtaining a good agreement between observed and calculated heads. The graph presented in figure 6 illustrates this good agreement. Errors values associated with this graph are reflected in table 3. The value of the normalized RMS is of 4.63% (< 10%) indicating that the model is well calibrated. The conditions provided by the modeling in permanent mode (hydrodynamic parameters and heads) will be used as initial conditions to modeling by transient mode (Table 4).

Model Validation

The simulation in transient mode has executed in taking an account piezometric data provided in permanent regime as initial data (1978). This simulation allows validating the model by comparison between observed and simulated heads in 1992. The groundwater levels measured in 1992 were then compared with those calculated by the model. Nine piezometers existing in 1978 were still available in 1992 for the validation of model in transient mode the validation of the model in transient mode is confirmed by the diagram in figure 7 and the performance parameters of the model (Table 5). The proximity of the points representing piezometers in 1992 around the first bisectrix reveals well that the difference between calculated heads and those observed is not important. In fact, with a confidence interval of 95%, seven of the nine piezometers considered, are located inside of this interval, either 78%. The calculation of the correlation coefficient (R^2) has given 0,995 (near to 1). The model can therefore be regarded as calibrated and validated with these piezometers of 1992. Nevertheless, significant differences between observed heads in piezometers at Anonkoua kouté 2 (2.06 m), Niangon 1 (2.01 m) and Anyama-Adjamé (1.81 m) are to be noted. These differences are caused by the exploitation of drilling during the piezometric program and also due to piezometers which are located not far from the pumping stations.

Abidjan Aquifer Level Simulation

Initial Piezometry of Abidjan Aquifer

In order to reconstitute the initial piezometry of Abidjan aquifer before any exploitation, the model has been driven in steady-state mode without active any boreholes (Figure 8). This map shows an initial direction of groundwater flow from the North (55 m) to the South (1 m) (toward Ebrié lagoon). The groundwater flow direction is oriented to the rivers; Agnéby and Lamé. The heads oscillate between 55 m (North) and 1 m (South).

Abidjan Aquifer Level in 1978

The map of 1978 head was simulated by assigning to the existing well fields the rates of pumping from1960 to 1978 (Figure 9). These pumping have led disturbances of the water level of Abidjan aquifer around the well fields in operation (Plateau, Adjamé nord, Zone nord, Zone ouest and Zone est). The North, East and West of the model are not affected by these pumping. Water budget for that simulation is summarized in table 6. This table shows that the principal input of Abidjan aquifer is constituted by the precipitation recharge which is approximately 908 840 m^3/day. In

1978, the discharge by pumping reaches 169 920 m^3/day and represents approximately 19% of the inputs by precipitation recharge. These values show that pumping did not have a great influence on the aquifer level because there was only five pumping stations in 1978 (Plateau, Adjamé nord, Zone nord, Zone ouest and Zone est) including 36 exploited boreholes (SOGREAH, 1992).

Piezometry and Abidjan Aquifer Drawdown In 2005

Piezometry and Abidjan aquifer drawdown in 2005 has been carried out by updating the pumping rates of the various well fields (Figures 10 and 11). A modification of the piezometer curves in relation to those of 1978 is observed to Anonkoua kouté, Niangon and especially to Riviéra (Centre and Nord). These changes are due to the development of the pumping stations of Anonkoua kouté, Niangon and Riviéra (Centre and Nord). After 27 years of Abidjan aquifer exploitation (year 2005), the drawdown are only observed around the well fields of Anonkoua kouté and Riviéra (Nord and Centre). The cones of drawdown (1 m) appear around pumping stations of Zone nord and Zone est (Figure 11). Except these important observations, the head remained unchanged on the whole model in relation to the reference year (1978). The piezometry values and drawdown calculated into the nine piezometers from 1978 to 2005 are shown in table 7. The higher value of the drawdown has been observed to the piezometer of Anonkoua kouté 2 (14.32 m) while Akakro (1.57 m), Anyama-Adjamé (2.66 m) and Akouédo (3.31 m) piezometers have the lowest values. The drawdown calculates into piezometers localized on the well fields is therefore function of the increasing of withdrawals between 1978 and 2005. The water shortages observed in the last few years in Abidjan can be explained by technical breakdowns but also by drawdown of water level into boreholes due to the strong flow taken per day. This drawdown can involve the pump draining of borehole causing its stop. Since the beginning of Abidjan aquifer operations in 1978, it has been of enormous drawdown. The more recorded water reduction in 2005 is observed into Anonkoua kouté 2 piezometer; with 14.32 m of drawdown.

Piezometry Evolution and Calculated Drawdown of Abidjan Aquifer from 2005 to 2030

The predictive simulations of Abidjan aquifer piezometry have been made in transient mode from 2005 with projected pumping rates between 2005 and 2030 by the SODECI. The piezometric maps (2015, 2020 and 2030) have been produced and are illustrated in the figure 12.

The analysis of piezometry evolution from 2005 to 2030 present modification of head contour lines and groundwater flow directions. The following observations are interpreted from the results. The modifications observed in 2005, compared to contour head calculated in 1978 are accentuated during 2015-2030. On figures 7a and 7b, modifications are translated by :

- projection of head contour line 5 m above Riviéra (centre and nord), Zone est and Zone nord stations;
- appearance of depression piezometric cone of 1 m around Riviéra (Centre and Nord) stations;
- progression of head contour line 25 m up to Anonkoua Kouté station

On figure 7c, the modifications are reflected by:

- projection of head contour line 1 m on the southern part of the model;
- clear localization of head contour line 25 m above Anonkoua Kouté station;
- progression of curve 1 m above Zone nord station.

North, east and west parts of Abidjan aquifer are little disturbed by the increase of the pumping stations for the period 2005-2030. In these parts of the model, there is no exploited borehole with a high flow rate. Only the model zone occupied by the majority stations is most disturbed.

Water budget arising from these simulations (Table 8) shows a dramatic increase of the input data from the model. The analysis of the table shows that the discharges are increased from 256 490 m^3/day in 2005 to 314 750 m^3/day, an increasing of 18 %.

It is clear from this table that the project of water withdrawals increasing by the SODECI to satisfy Abidjan population is possible until 2030. This increase is conditioned by the various assumptions made in the context of this work:

- The constancy of the recharge (247.7 mm/day) until 2030 ;
- The recharge uniformity on the whole Abidjan aquifer.

However most drawdowns of the water level into Abidjan aquifer have been observed in some places. The predictable water levels into piezometers are recorded in table 9.

From predictable water level into piezometers, the drawdown of the aquifer in relation to 1978 piezometric data corresponding to the situation of the aquifer in permanent regime, has been mapping (Figure 13). It stand out from this figure that after 37 years of exploitation (year 2015), the drawdown contour of water level of Abidjan aquifer is near of Anyama-Adjamé and Akouédo piezometers respectively at the pumping stations of Anonkoua kouté and Riviéra Nord (Figure 13a). The circumscription by the drawdown contour (1 m) of the pumping stations of Zone (Nord and Est) is now clear. On the figure 13c, this contour progressed and reached piezometers of Anyama-Adjamé (in North), of Akouédo (in South-east) and Filtisac (the Centre) after 52 years of exploitation i.e. 2030. The circumscription by the drawdown of well fields; Anonkoua kouté, Niangon, Zone Nord, Riviéra Centre, Nord-Riviera, Zone Est; shows that those are interfered mutually. Thus, any other installation of boreholes or pumping stations inside this area is not recommended because it could increase the drawdown contour. This increase could cause a significant decrease of water level of certain boreholes.

The flow rates of exploitation provided by SODECI will certainly have an impact on water level of Abidjan aquifer. To face the high demand in water of Abidjan population, surfaces to be exploited for installation of new boreholes or pumping station should be localized in the south-east or east of Riviéra Nord station and the west of Niangon station. Inside these surfaces, drawdown contour projected is remains very low during the simulation. The drawdown contour of the water level of Abidjan aquifer delimits the zone of influence of pumping stations. The limit of these zones corresponds to the distance where the drawdown caused by pumping is negligible.

Drawdowns calculated into piezometers are recorded in the table 10. This table shows that all the piezometers underwent a drawdown, because all calculated values are higher than 1 m. It is clear that groundwater retrieval since 1978 greatly influenced the water level of Abidjan aquifer. These values vary between 1 (Akakro) and 15.71 m (Anonkoua kouté). The highest drawdown (higher than 5 m), observed after 52 years of exploitation (2030) was noticed:

- at Anonkoua kouté 2, 15.71 m with a drawdown rate of 30.21 cm/year;
- at Niangon 1, 6.86 m with 13.19 cm/year as drawdown rate;
- at Adonkoua, 6.24 m with 12 cm/year as drawdown rate;
- at Zoo 2, 5.44 m with a drawdown rate of 10.46 cm/year.

DISCUSSION

The modeling is a prediction and calculation tool and its precision depends on the reliability of the integrated data (Leduc, 2005). Abidjan aquifer model has been produced from historical data (geological, hydrogeological, piezometric). It had done to simulate the piezometric level and to calculate the drawdown of the aquifer between 2005 and 2030. The model designed works in steady-state and in transient mode. From 1978 piezometric data, the model was calibrated in steady-state mode. The calibration of the model gave a NRMS of 4.63%, indicating that the model is well calibrated. The setting of Abidjan aquifer piezometry from this model has shown that the groundwater of the aquifer flowing from the North to the South and to the lagoons Adjin and Agnéby. This diection is imposed by the hydraulic heads which oscillate between into the north piezometers between 55 and 40 m while those in the South between 0 and 5 m. The similar studies conducted by SOGREAH (1992), HYDROEXPERT (2001) and Sombo (2006) have shown in a general way that Abidjan aquifer waters flowing from the North to the South. The manual calibration has also been employed by Sombo (2006) and the results are uniform with those obtained in this study in steady-state mode. The transient mode developed has been calibrated from original data of 1978 and valid on the basis of 1992 piezometric data. The calibration results have given 2.78% as the value of the NRMS. The drawdowns calculated from the model, caused by the increasing of withdrawals, will oscillate between 1 and 16 m in 2030 by taking 1978 as the reference year. The west and south-east parts of the model have been weakly influenced. The water budget has shown that rain is the origin recharge of the aquifer and the withdrawals will increase from 256 490 m^3/day (2005) to 310 760 m^3/day (2030), an increase of 18%. This increasing provided by SODECI, from 2005 to 2030, is possible in the light of obtained results. But it will have an impact on the water level of Abidjan aquifer. The highest drawdowns were observed into the piezometers of, Anonkoua kouté 2 with 15.71 m, Niangon 1 with 6.86 m and Adonkoua with 6.24 m. The values of drawdowns obtained seem to reflect the actual behavior of the aquifer. However, the assumption on the constancy and recharge uniformity (2005-2030) seems to be an optimistic condition, in referring to the climatic conditions and especially to the current expanding urbanization of the study area (Kouamé *et al.*, 2008). This urbanization can make the ground impermeable. Thus, the hypothesis that, aquifer recharge would remain constant during the whole simulation and would be evenly distributed, does not reflect completely the reality of the situation on the ground at any place. These drawdown values can therefore be considered to be those that will justify this assumption. The contour of drawdown obtained in 2030 progress toward the lagoons (Adjin, Ebrié, Lamé). This behavior of that contour can cause a saline intrusion if the rates provided by SODECI are able to reverse the groundwater flow direction (which of course is very rare). However, it seems that the risk of an advance of the bevel salted is possible, but a good repartition of future boreholes could reduce the drawdown as well as the probabilities of groundwater contamination by saline intrusion. A network observation points for salinity monitoring is therefore necessary primarily in the south of the aquifer.

CONCLUSION

Groundwater modeling flow of Abidjan aquifer has been designed on a regional scale. The analysis of the hydrodynamic behavior model has clearly shown that the withdrawals increasing project from 2005 to 2030 to satisfy the water supply of Abidjan District is possible. These withdrawals will pass from 256 490 m^3/day (2005) to 310 760 m^3/day (2030). However, it is important to remember that the highest drawdowns were observed into the piezometers, Anonkoua kouté 2 (15.71 m), Niangon 1 (6.86 m) and Adonkoua (6.24 m). This model helped to determine the west and south-east areas as favorable sites for the implantation of new boreholes, with reasonable flow rates.

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Table-1. Rates of pumping stations from 1960 to 1978 (Sombo, 2006)

Pumping stations names	**Withdrawals (m^3/day)**
Anonkoua kouté	0
Zone nord	24 000
Adjame nord	37 680
Niangon	0
Zone ouest	49 200
Zone est	29 040
Nord Riviera	0
Riviera Centre	0
Plateau	1 800

Table-2. Rates of pumping stations from 1978 to 2030 (in m^3/day)

Stations	**1978 1980**	**1980 1985**	**1985 1995**	**1995 2000**	**2000 2005**	**2005 2015**	**2015 2030**
Anonkoua Kouté	0	28 296	21 960	31 440	38 000	43 000	43 000
Zone nord	24 000	30 000	25 824	32 592	34 992	37 000	37 000
Adjamé nord	37 680	31 680	13 848	20 880	9 300	27 480	27 480
Niangon	0	28 800	33 000	40 608	37 000	48 000	48 000
Zone ouest	25 200	31 200	37 488	37 920	48 000	50 000	50 000
Zone est	38 304	26 784	28 776	32 304	33 000	43 992	43 992
Nord Riviéra	0	36 000	32 496	33 062	38 000	43 992	43 992
Riviera centre	0	9 984	16 704	19 992	20 000	21 288	21 288
Plateau	30 000	24 000	1 800	1 368	194	0	0

Table-3. Calibration statistics in steady-state from 1978 data

Errors	Symbol	Values
Residual mean (m)	$\overline{R}$	-1.90
Absolute Residual mean (m)	$\lvert\overline{R}\rvert$	2.17
Standard Error of the Estimate (m)	SEE	0.25
Root Mean Squared residual (m)	RMS	2.56
Normalized Root Mean Squared residual (%)	NRMS	4.63

Table-4. Adjusted hydrodynamic parameters of Abidjan aquifer

Hydrodynamic parameters	Initial values	Adjusted values
Hydraulic conductivity		
○ Coarse sand	4.10^{-4} m/s	5.10^{-4} m/s
○ Fine sand	10^{-4} m/s	2.10^{-4} m/s
Effective porosity	1.5%	2 %
Specific yield	15 %	20 %

Table-5. Calibration statistics in transient state from 1992 data

Errors	Symbol	Values
Residual mean (m)	$\overline{R}$	-0.45
Absolute Residual mean (m)	$\lvert\overline{R}\rvert$	1.15
Standard Error of the Estimate (m)	SEE	0.45
Root Mean Squared residual (m)	RMS	1.35
Normalized Root Mean Squared residual (%)	NRMS	2.78

Table-6. Water budget calculated after steady state calibration in 1978

Input	m^3/day	Output	m^3/day
Constant head	290 390	Constant head	589 280
Well	0	Well	169 920
Recharge	90 8840	Recharge	0
River leakage	34 870	River leakage	475 000
Total	1 234 100	Total	1 234 200

Table-7. Piezometry and Drawdown calculated into piezometers compared to 1978 piezometric data

	Piezometry calculed in meter		Drawdown in meter
Piezometers	1978	2005	2005
Adonkoua	25.06	18.85	6.21
Akouédo	6.13	2.82	3.31
Anonkoua kouté 2	42.36	28.04	14.32
Anyama-Adjamé	49.52	46.86	2.66
Filtisac	19.62	15.83	3.79
Niangon 1	13.80	8.76	5.04
Zoo 1	11.75	7.47	4.28
Zoo 2	19.23	14.33	4.90
Akakro	2.34	0.77	1.57

Table-8. Water budget calculated after exploitation in transient mode from 2005 to 2030

Input	m^3/day	Output	m^3/day
Storing	130 470	Storing	0.02
Contributions by the loads imposed	262 790	Losses by the loads imposed	572 340
Well	0	Well	314 750
Recharge	908 840	Recharge	0
River leakage	37 100	Exfiltration to the rivers	452 110
Total	1 339 200	Total	1 339 200

Table-9. Predictable water level into piezometers in meter

Piezomters	1978 (relevant year)	2015	2020	2030
Adonkoua	25.06	18.84	18.84	18.82
Akouédo	6.13	2.71	2.63	2.49
Anonkoua kouté 2	42.36	27.07	26.87	26.65
Anyama-Adjamé	49.52	46.60	46.53	46.44
Filtisac	19.62	15.58	15.43	15.18
Niangon 1	13.80	7.81	7.42	6.94
Zoo 1	11.75	7.40	7.28	7.05
Zoo 2	19.23	14.11	14.00	13.79
Akakro	2.34	0.77	0.77	0.77

Table-10. Drawdown calculated into piezometers compared to 1978 piezometric data

Piezometers	Drawdown (m)		
	2015	2020	2030
Adonkoua	6.22	6.22	6.24
Akouédo	3.42	3.5	3.64
Anonkoua kouté 2	15.29	15.49	15.71
Anyama-Adjamé	2.92	2.99	3.08
Filtisac	4.04	4.19	4.44
Niangon 1	5.99	6.38	6.86
Zoo 1	4.35	4.47	4.7
Zoo 2	5.12	5.23	5.44
Akakro	1.57	1.57	1.57

Figure-1. Location of Abidjan district

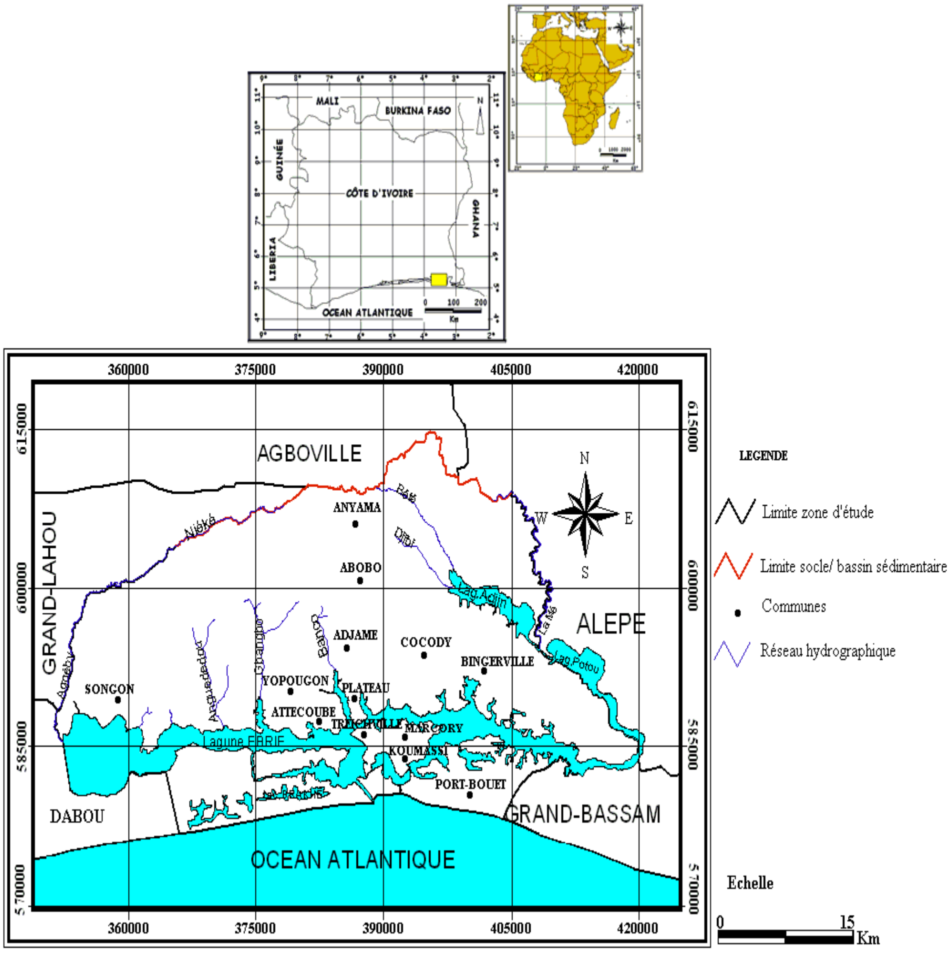


Figure-2. Cut north-south of the Ivorian coastal sedimentary basin (Jourda, 1987)

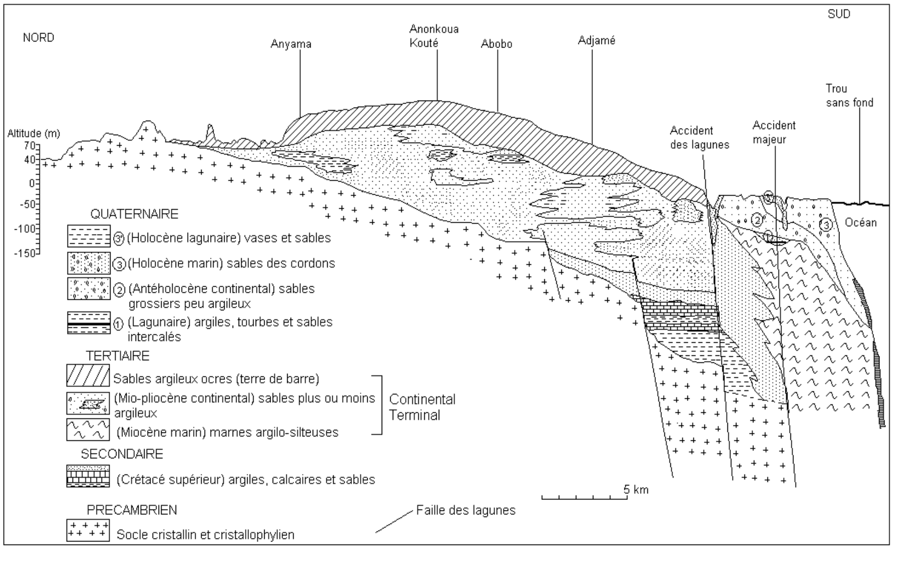


Figure-3. Flow chart for the design of the numerical model of Abidjan aquifer

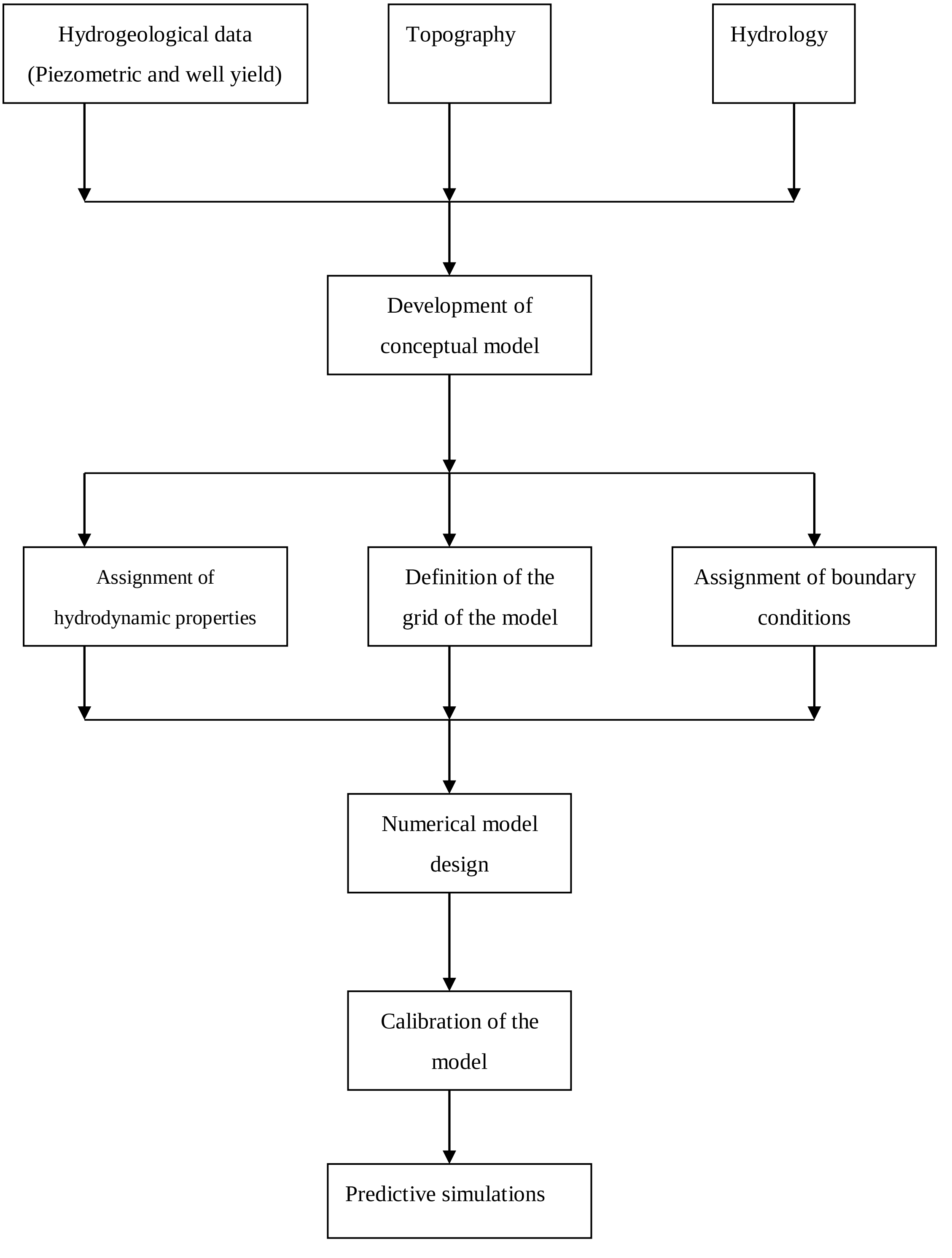


Figure-4. Grid of the numerical model

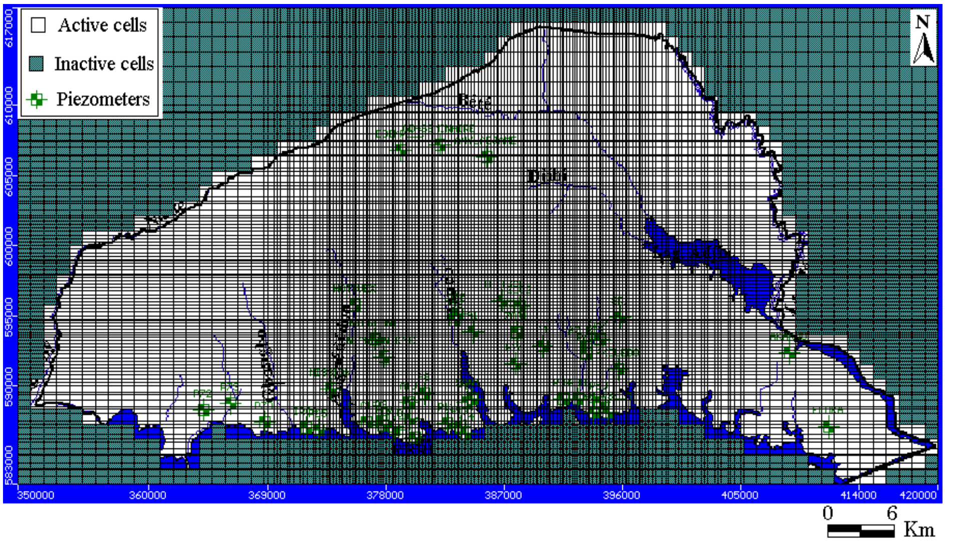


Figure-5. Boundary conditions of the model

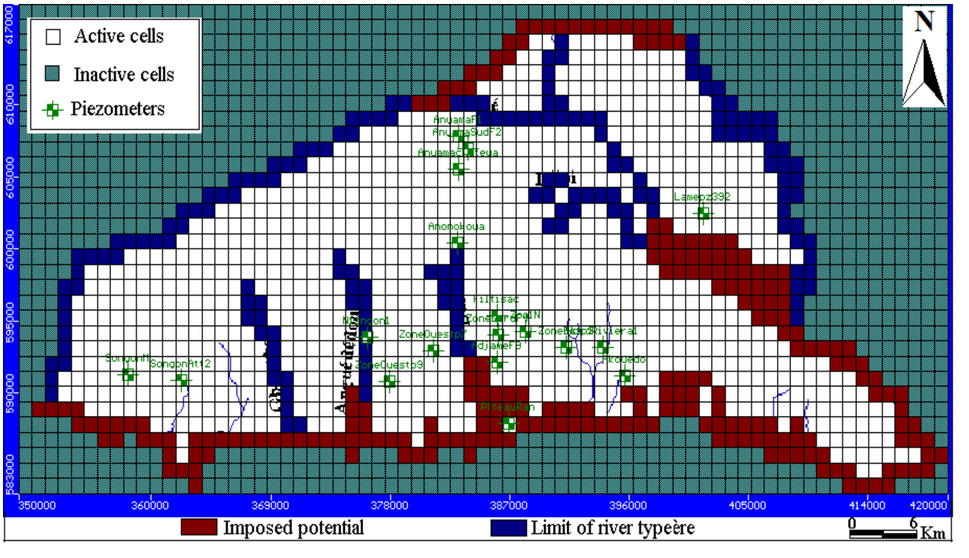


Figure-6. Graph of calculated heads *vs.* observed heads in permanent mode

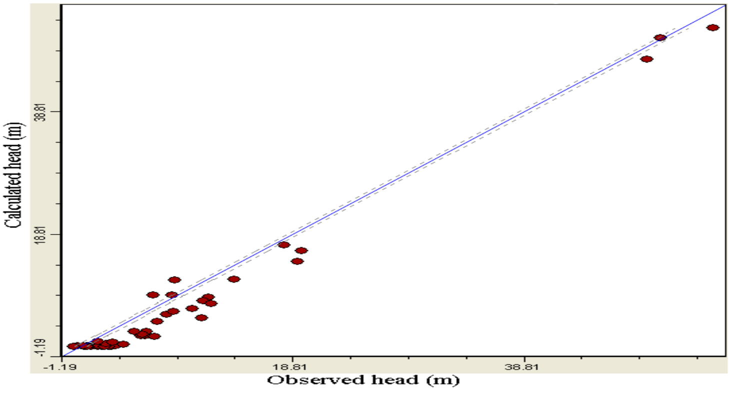


Figure-7. Graph of calculated heads vs. observed heads in transitory mode in 1992

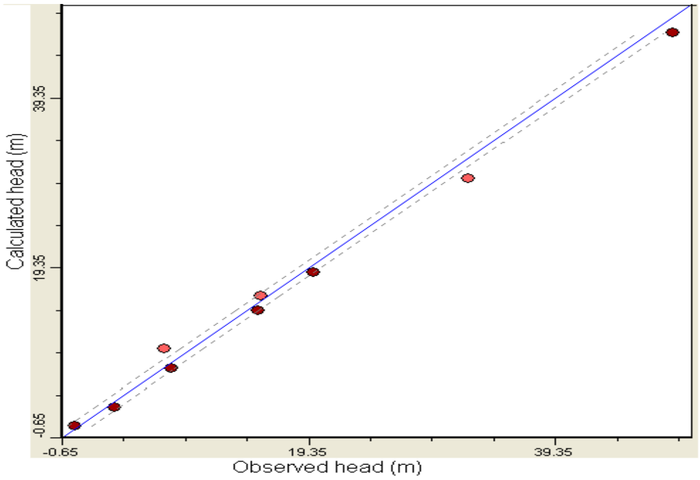


Figure-8. Initial contour head reconstructed in permanent mode (year 1960)

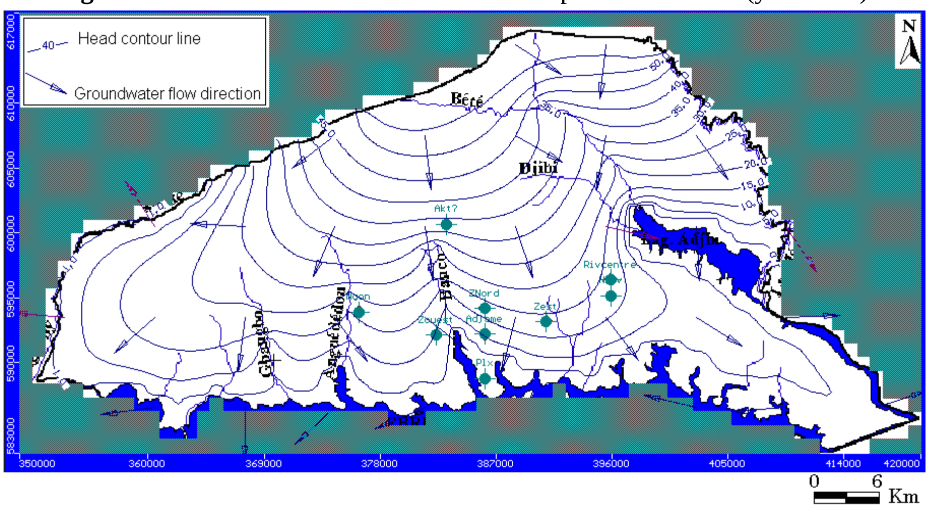


Figure-9. Piezometry calculated in 1978 in permanent mode

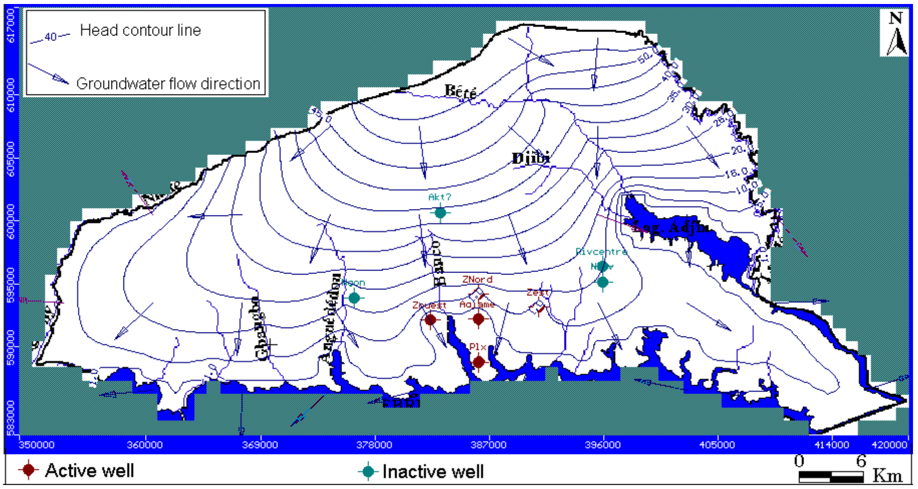


Figure-10. Piezometry calculated in transient state flow mode for 2005

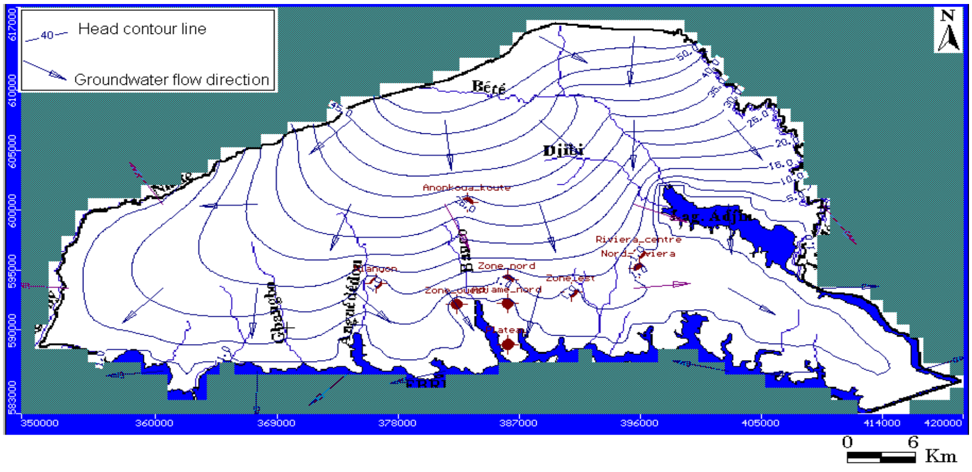


Figure-11. Drawdown calculated in transient state flow mode for 2005

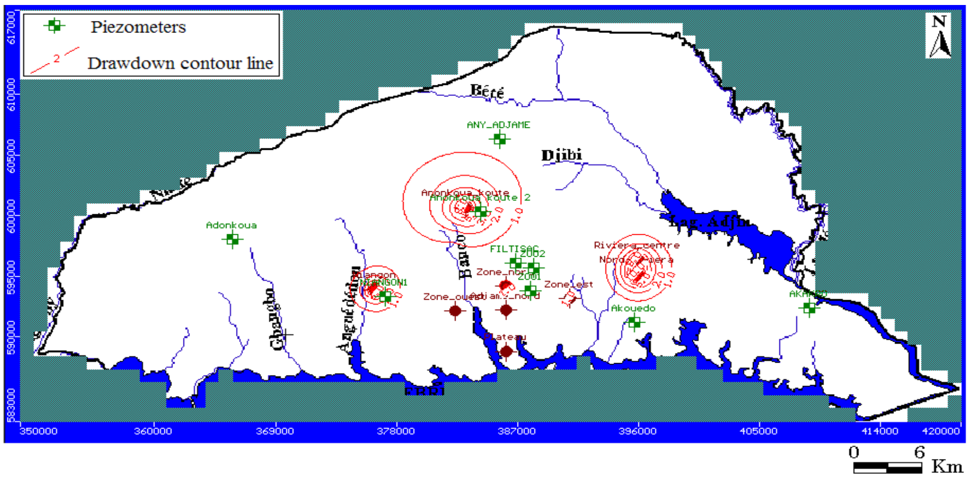
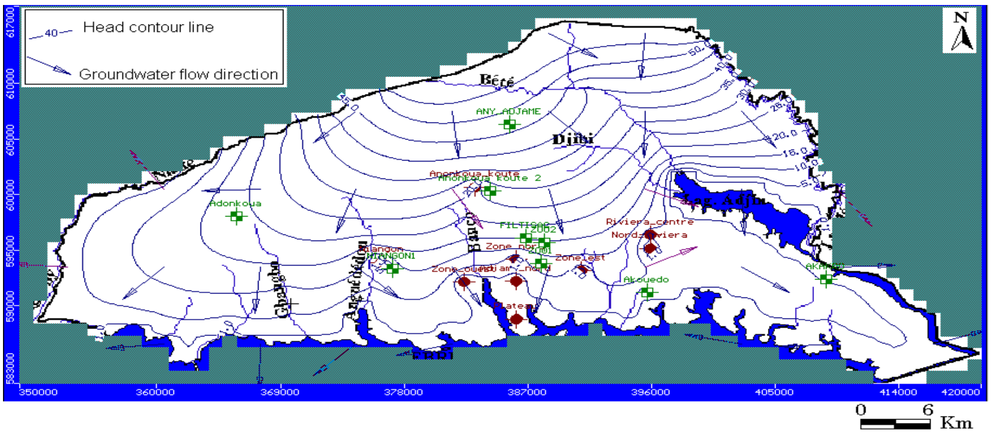
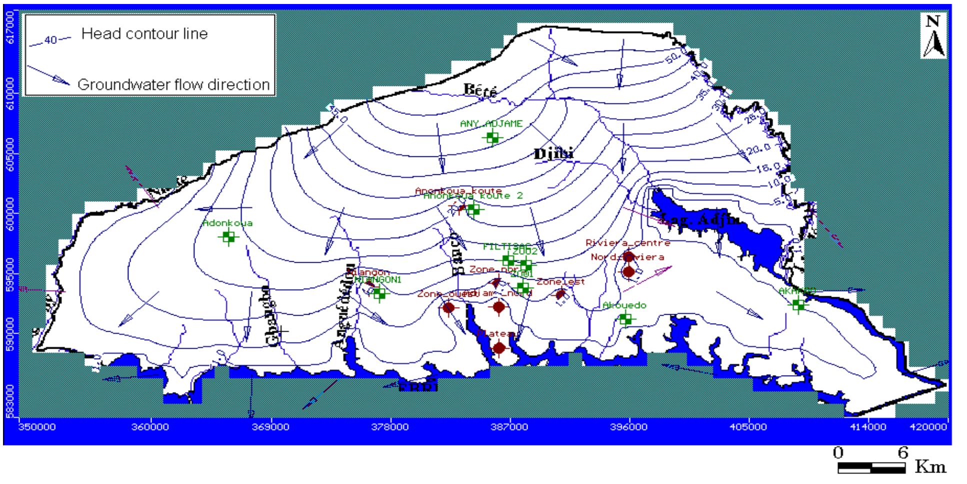


Figure-12. Maps showing differences of calculated piezmetric head in the aquifer: a) 2015; b) 2020; c) 2030



(A)



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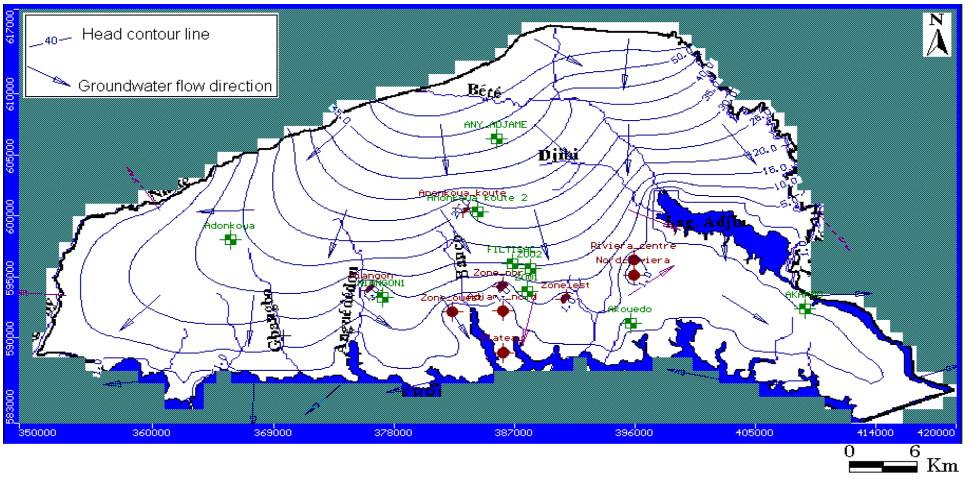
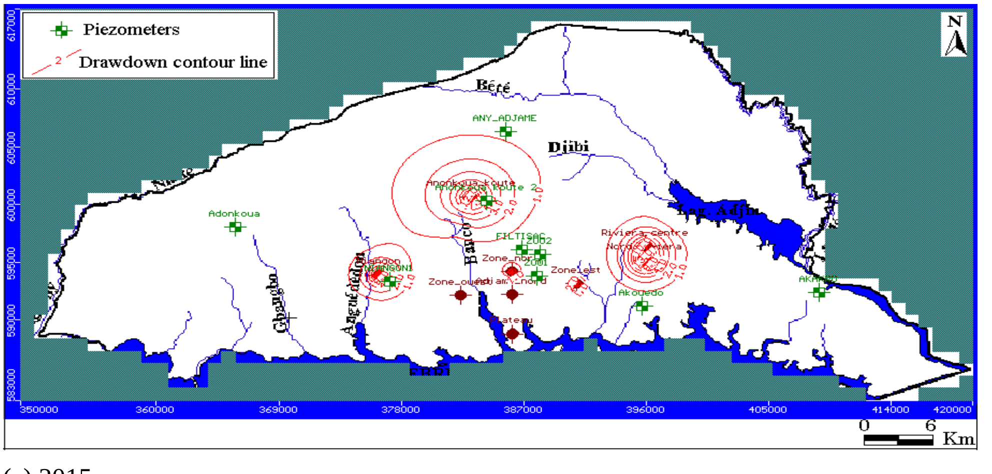
(B)

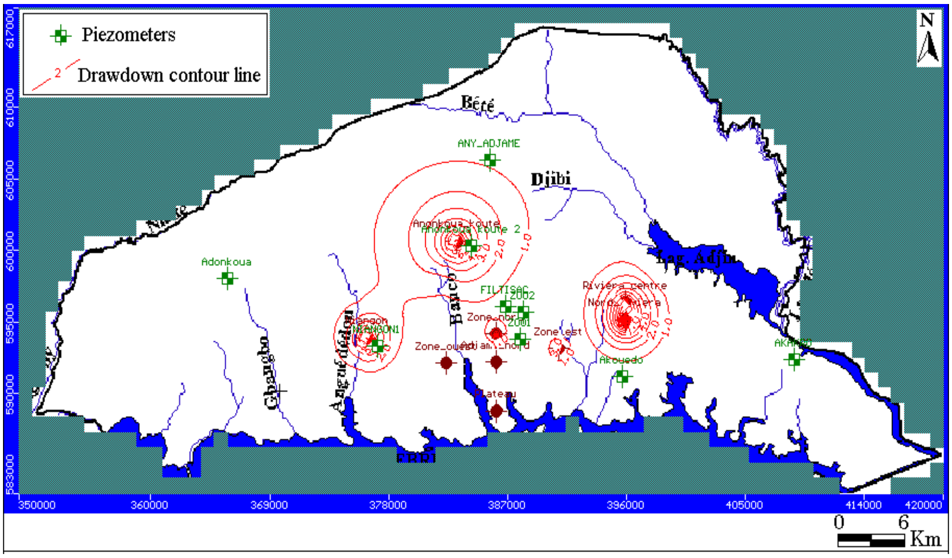


(C)

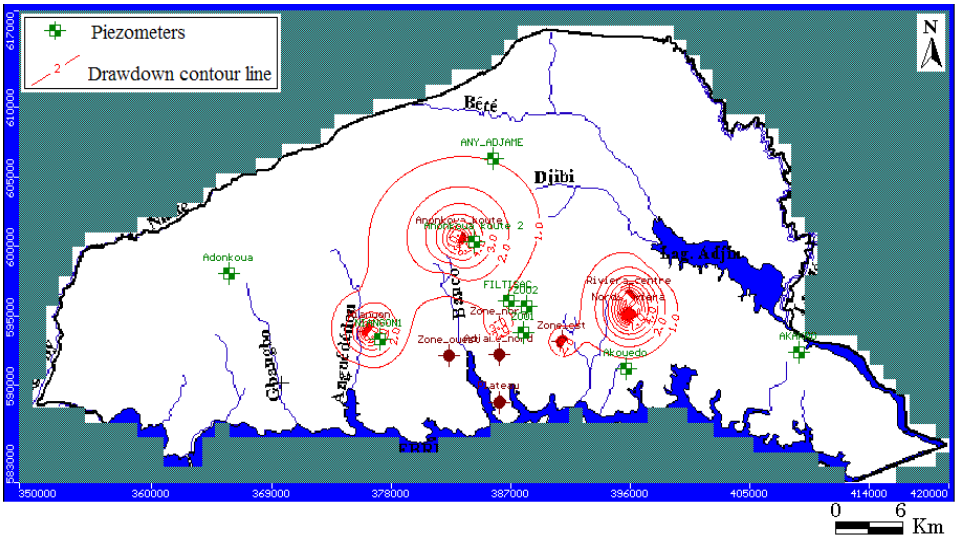
Figure-13. Maps showing the drawdown evolution in the aquifer: a) 2015; (b) 2020; (c) 2030



(a) 2015


Piezometers
Drawdown contour line
N
Bété
ANY_ADJAME
Djibi
Adonkoua
Banco
Lag. Adjin
Riviera_centre
Zone_est
Zone_ouest
Plateau
Akouedo
350000
360000
369000
378000
387000
396000
405000
414000
420000
617000
610000
605000
600000
595000
590000
583000
0
6
Km

(b) 2020


Piezometers
Drawdown contour line
N
Bété
ANY_ADJAME
Djibi
Adonkoua
Banco
Lag. Adjin
Riviera_centre
Zone_est
Zone_ouest
Plateau
Akouedo
350000
360000
369000
378000
387000
396000
405000
414000
420000
617000
610000
605000
600000
595000
590000
583000
0
6
Km

(c) 2030