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Hydrogeological Characterization and Hydrodynamic Behaviour of the Overexploited Diass Aquifer System (Senegal) Inferred from Long Term Groundwater Level Monitoring

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Abstract Dakar, the Capital city of Senegal concentrates about 23.2% (about 3 millions inhabitants) of the total population [1] and a large proportion of the industrial activities. Water supply is ensured by surface water pumped and piped from the Guiers Lake (250 km distant from the capital) and from groundwater resources. Among these latter, the Diass aquifer system contributes to a substantial proportion (31% in 2019) of the total water supply distribution due to growing demand induced by the rapid demographic growth (about 2.5%). The Diass horst aquifer system located 50 km east of Dakar (Senegal) is exploited with two main aquifers covered by a sandy superficial aquifer: the confined/unconfined Palaeocene karstic limestone and the confined Maastrichtian sandstone aquifer underneath. This system has experienced intensive groundwater abstraction during the last 60 years to meet the increasing water demand. Abstraction for urban drinking water occurs in nine pumping fields with a rate reaching 174,000 m^3/d in 2019. This high yield together with the drought conditions since the 1970s is likely to affect groundwater imbalance and change the flow regime. The objective of the study is to improve our understanding of the system dynamic with regards to the high pumping rate in order to build a conceptual scheme for further hydrogeological modeling of the system. In this study, we use monitored pumping rates, piezometric level from 1960s to 2019 and rainfall data from 1931 to December 2016 together with the hydrogeological configuration to infer the dynamics of the aquifer system. The high abstraction rate during the period 1958-2019 which vary from 16,000 to 174,000 m^3/d has caused a continuous groundwater level decline (up to 30 m), a modification of the flow patterns and to some extent a quality deterioration through salinization processes as shown in a few boreholes in Sébikotane and Mbour. The piezometric levels which were above the sea level prior 1959 exhibit now negative values and can even reach -40 m in the vicinity of the pumping fields creating therefore piezometric depressions and convergent flow pattern. The hydrodynamic of the system derived from the results show that the reservoir acts as a multilayer aquifer system with interconnected compartments by faults that allow flux exchanges except the confining Ponty and Sébikotane faults. Overexploitation inducing important drawdown has induced an increase of the drainance fluxes between those different compartments [2]. In order to foster more appropriate and sustainable groundwater abstraction in the complex hydrogeological system with regards to demand and water quality conservation, it is important to assess the main system behavior.

Keywords: *aquifer overexploitation, hydraulic head, groundwater pumping, flow exchange, recharge, Palaeocene, Maastrichtian, Diass horst*

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1. Introduction

In semi arid and arid regions characterized by low and variable rainfall, groundwater resource is often the only source of drinking water since surface waters are scarce or not available. Rainfall spatial and temporal distribution in these regions is highly variable and since the 1970s, a rainfall deficit occurs like in most parts of the Sahel zone [3,4,5]. As a consequence, deficits in groundwater recharge are observed [2,6] as well as variations and changes in the hydrologic and hydrogeological systems [7,8,9]. In these regions, intensive exploitation of groundwater resources to meet increasing water demand may occur. This is the case for Dakar, Capital city of Senegal where a highwater demand is due to an exponential demography. Consequently, increasing groundwater exploitation corresponds to the occurrence of drought conditions since the 1970s.

As evidenced in many studies, high groundwater abstraction rates induce a continuous groundwater level decline, a modification of the groundwater flow patterns and deterioration of groundwater quality through salinization [10,11,12,13,14,15].

The Diass horst aquifer system, as an important water supply reservoir for drinking water for the Dakar region and surrounding areas of Pout, Sébikotane, Mbour and also for industrial and agricultural activities needs was the focus of several studies since the early 1970’s [15]. Pumping began in December 1958 in the Sébikotane Palaeocene limestone compartment. The total abstraction rates were initially around 16,000 m³/day and gradually increased to reach 174,000 m³/day in 2019 distributed over the pumping fields in Sébikotane, Bayakh, Thieudeum, Diass, Northern Pout, Southern Pout, Mbour, Thiès and Tasset. This high yield has caused a continuous groundwater level decline (more than -30 m in 50 years) mostly observed in Sébikotane and Northern Pout compartments, a change in the groundwater flow and quality patterns which are evidenced by salinization of some boreholes located at Sébikotane and Mbour pumping fields [2]. Moreover, the period coincides with the occurrence of drought climatic conditions since the 1970’s (lowering of rainfall to about 34%) reducing groundwater recharge in the region. Therefore, historical data records from previous periods (prior to the current pumping conditions) offer the possibility to analyze the flow dynamics with regards to temporal anthropogenic stresses.

The present study aims to improve our understanding of the groundwater flow dynamics in order to foster more appropriate groundwater management with regards to high exploitation in the Diass aquifer system and to build a realistic conceptual model useful for future groundwater modeling. Specifically, the study aims to evaluate: 1) the groundwater spatial and temporal flow regime; 2) the possible lateral and vertical groundwater exchange flows; 3) the groundwater recharge variation. Results would help to evaluate the degree of vulnerability of this aquifer system to future pumping and to foster a management tool to ensure sustainability of this important groundwater resource.

2. Study Area Description

The study area is located in the western part of Senegal between Dakar and Thiès regions and extends over a surface area of 1,340 km² (Figure 1).

2.1. Geomorphology and Soil Types

In the area, the reliefs are generally moderately high (Figure 1). From the geomorphological point of view, we schematically note three sectors.

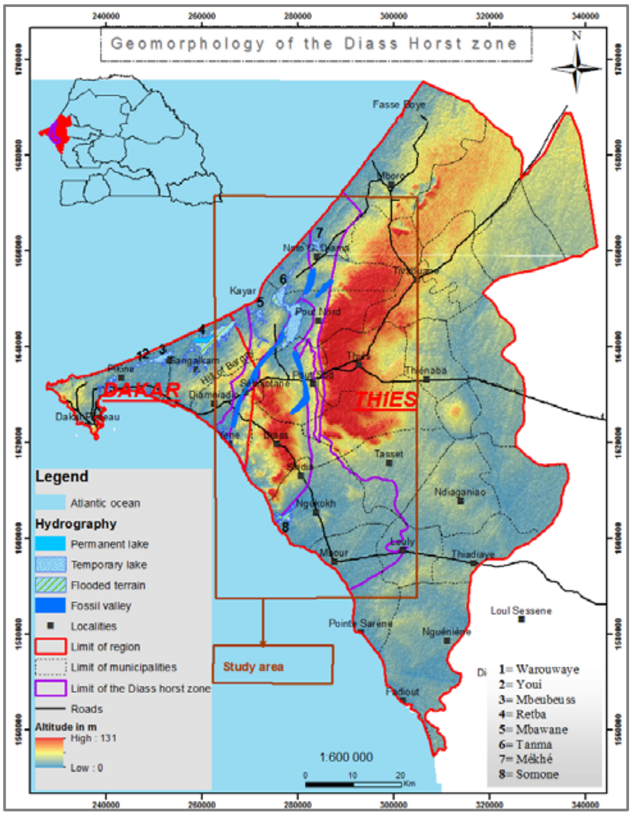


Figure 1. Geomorphology of the Diass horst zone

- **the extreme western sector** corresponding to the Cape Verde peninsula, where a maximum altitude of 105 m is noted at the ‘Mamelles Volcano’.
- **the central and northern sector**, limited to the west by the Quaternary volcanism and to the east by the Sébikotane fault, corresponds to the depressed dune zone where average altitude is between 20 and 30 m, and reaches 50 to 60 m at the Bargny plateau.

This sector is characterized by an alignment of old dunes oriented NE-SW; the presence of ‘Niayes’ (which are lacustrine depressions where the water table outcrops) is observed forming a succession of lakes. The latter formed the main water surface bodies and are named successively from West to East: Warouwaye (1), Youi (2), Mbeubeuss (3), Retba (4), Mbawane (5), Tanma (6), Mékhé (7) and Somone (8) in the Southern part. Their altitude is about 0 m and they are now dried except the Retba lake which is -2.5 m. Fossils valleys are Ndoyène and Pout (Figure 1).

- **The eastern sector** corresponds to the Diass horst, object of this study and to the plateau of Thiès with respective maximum altitudes of 90 and 131 m. In the northern and southern parts of the Sébikotane and Pout compartments, the altitude varies from 0 to 30 m and from 30 m to 50 m on the Bargny plateau and reaches 90 m in the Diass compartment.

In the Sébikotane and Pout compartments, soils are mainly: tropical ferruginous soils, poorly evolved soils and raw mineral soils consisting of siliceous sands, hydromorphic soils on various materials or silty alluviums and black sandy clay. On the Diass compartment, soils are mainly lateritic in high altitude and tropical ferruginous soils at low altitude.

2.2. Spatial and Temporal Distribution of Climatic Data

The study area is characterized by a tropical climate with two distinct seasons: a dry season (from November to May) and a rainy season (from June to October). Climatic data (temperature, relative humidity, insulation and wind speed) during the period from 1977 to 2001 and precipitation from 1931 to 2016 were collected from the Senegal National Meteorological Agency in Thiès and Mbour weather stations. The average annual precipitation and temperatures are 440 mm/yr and 27°C respectively. Rainfall spatial and temporal distribution is highly variable and since the 1970's, a rainfall deficit occurs through most of the Sahel zone [3,4,5].

The 'Standardized Precipitation Index' which is an average of the centered and reduced seasonal rainfall allows analyzing the temporal variability of precipitation and therefore to identify wet, average or dry years over a given period. This index was computed from rainfall data between 1931 and 2016 in the Thiès and Mbour rainfall stations and shows a pronounced rainfall deficit from 1971 (Figure 2). However there are two distinct periods:

- a "wet period" from 1931 to 1970 where the average annual rainfall is 664 mm/year at Thiès and 762 mm/year at Mbour;

- a "deficit period" from 1971 to 2016 where the average annual rainfall is respectively 432 mm/year and 512 mm/year at Thiès and at Mbour.

Potential and actual evapotranspiration calculated using the Penman method [16] (1977 to 2001) are 2057 and 371 mm/yr, respectively [2].

2.3. Geology and Hydrogeology

The geological structure of the system is updated using hydraulic and petroleum boreholes data, cross sections [17,18,19] and geological map (1/50,000) established recently [20]. The system is limited by the Ponty fault in the West, the Atlantic Ocean in the North and South and the Thiès fault in the East. Table 1 summarizes the main geological and hydrogeological characteristics in the aquifer system and the map in Figure 3a presents the top main aquifer.

The Diass aquifer system consists of a complex multilayer structure, subdivided into compartments by four major faults oriented NE-SW (Figure 3a). These faults configure the region into a horst system with three compartments: the Diass compartment in the center (between the Sébikotane and Pout faults) where the Maastrichtian sandstones outcrop, surrounded by two Palaeocene karstic limestones compartments [17] namely the Sébikotane compartment in the West (between the Ponty and Sébikotane faults) and the Pout compartment in the East (between the Pout and Thiès faults) (Figure 3a).

The geological formations from bottom to top are composed as followed [17,18,19,20] (Table 1):

- the Maastrichtian formations being heterogeneous both laterally and vertically are composed of sandy clay with interbedded sand, calcareous sandstone and clayey sands at the top. Towards the West, they are mainly composed of clayey sediments.
- The Palaeocene formations consisting of a succession of marly and clayey limestones. The latter formations are karstified in the Sébikotane and Pout compartment while in the western part; they are made of clay and clayey limestone.
- the Eocene formations made up of marl and clay overlying the Palaeocene limestone in the Sébikotane and northern Pout compartments.
- the Mio-Plio-Quaternary sediments composed of clayey sand and laterites, they constitute the top formations (Figure 3b).

The system is composed of two main aquifers namely the Maastrichtian (lower aquifer) and the Palaeocene (middle aquifer) covered by the superficial Quaternary aquifer. Due to the structure of the horst system, these aquifers are also subdivided into three hydrogeological compartments: the Diass compartment in the center, the confined Sébikotane compartment in the West and the confined/unconfined Pout compartment in the East (Figure 3a). This layout is used geographically to divide the Pout compartment into three zones: the Northern Pout zone where the Palaeocene is overlaid by the marly Eocene, the Southern Pout area and the Mbour zone where the Palaeocene layer outcrops. The Maastrichtian aquifer which thickness increases from West (50 m) to East (450 m) is separated from the Palaeocene karstified limestone aquifer by the Danian marly limestone.

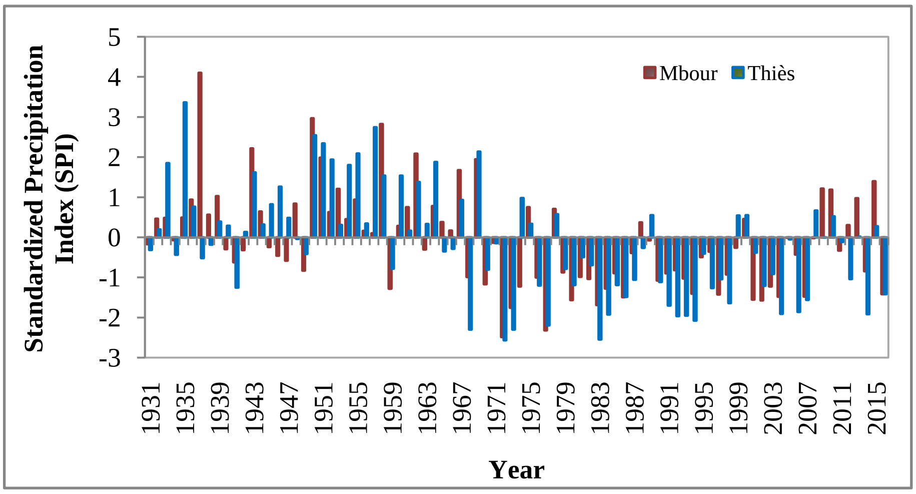


Figure 2. 'Standardized Precipitation Index' from 1931-2016

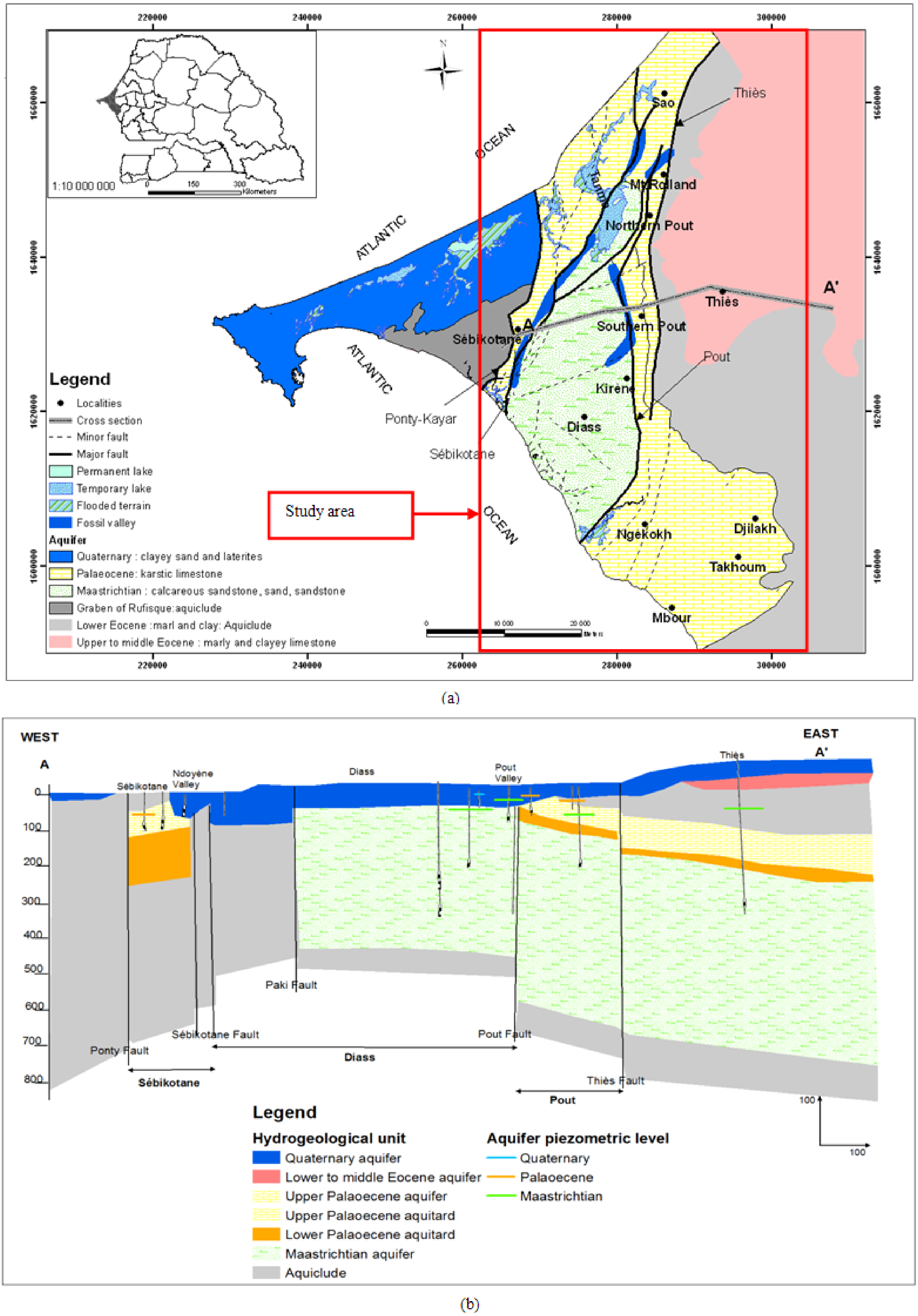


Figure 3. Hydrogeological map presenting the top main aquifers (a) and a cross section of the study area AA' (b) (modified from [17])

Table 1. Geological and hydrogeological characteristics of the aquifer system

Etage		Dominant lithology / Hydrogeological units /Hydrodynamic properties					
		Compartments					
		Sebikotane	**Diass**	**Northern Pout**	**Southern Pout**	**Mbour**	**East of the study area**
Mio-Plio-Quaternary		Clayey sand/Aquifer/K $\approx 1.5\times10^{-4}$; S = 20%					Clayey sand and laterites/ Aquifer
Eocene	**Upper to Middle**	Marl and clay/Aquiclude	No occurence	Marl and clay/Aquiclude	No occurence		Marly and clayey limestone/Aquifer
	Lower						Marl and clay/ Aquiclude
Palaeocene	**Upper to Middle**	Karstifiedlimestone/Aquifer	No occurence	Karstified limestone/Aquifer K= 6.64×10^{-6} to 2×10^{-2}; S = 1×10^{-4} to 7×10^{-2}			Not karstified limestone/Aquitard
	Lower (Danian)	Marly and clayey calcareous/ Aquitard		Marly and clayey calcareous / Aquitard			
Maastrichtian	**Upper and Middle**	Clay/Aquiclude	Sand, calcareous sandstone and clayey sand /Aquifer K= 1×10^{-5} to 1.9×10^{-3}; S = 1×10^{-4} to 6×10^{-4}				
	Lower		Clay with interbedded sand and sandstone/Aquiclude				
Campanian		Clayey sand/Aquiclude					

Hydraulic conductivity values range from 1×10^{-5} m/s to 1.9×10^{-3} m/s and the storage coefficient values from 1×10^{-4} to 6×10^{-4} (Table 1) [19,21,22,23,24]. In the Palaeocene karstic limestone aquifer, hydraulic conductivity values are highly variable and range from 6.64×10^{-6} to 2×10^{-2} m/s. The storage coefficient varies from 1×10^{-4} to 7×10^{-2}. In the Mio-Plio-Quaternary aquifer, mean values of hydraulic conductivity and effective drainage porosity are about 1.5×10^{-4} m/s and 20%, respectively [21].

2.4. Groundwater Pumping

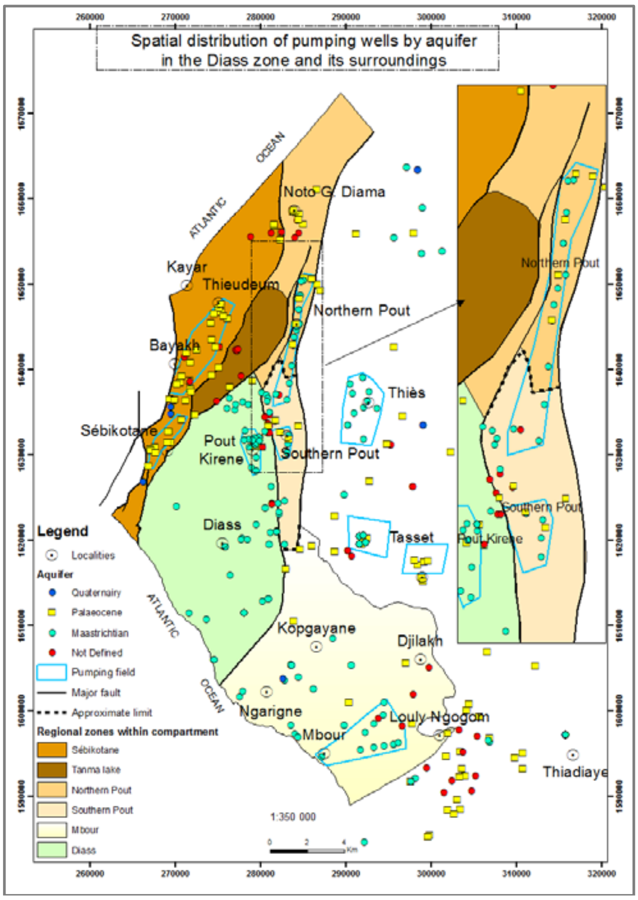


Figure 4a. Spatial distribution of pumping wells in the Diass zone and its surroundings

The aquifer system and its vicinity zones of Thies and Tassette are highly exploited for the following uses:

- urban drinking water managed by the National Water Company,
- rural drinking water managed by the rural water supply company,
- private use mainly driven by agricultural needs,
- industrial uses (mining, agro-food industries).

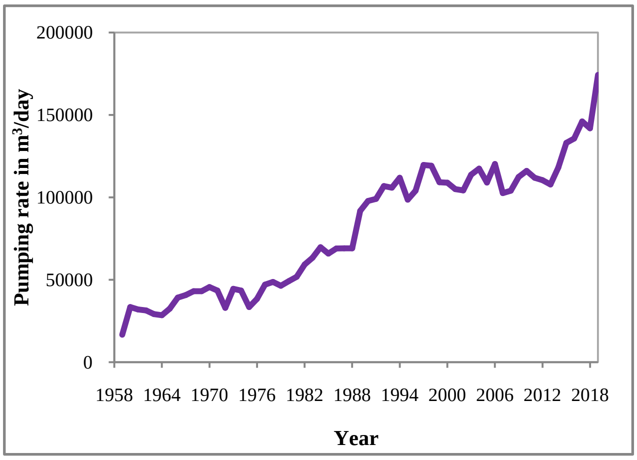


Figure 4b. Evolution of daily pumping rate for urban drinking water from the Diass system

The spatial distribution of boreholes tapping the different aquifers (Figure 4a) shows their high density, especially for the Palaeocene and Maastrichtian aquifers which are the most exploited aquifers. Total pumping rate at the Diass horst and in its surroundings areas (Thiès, Tasset) are estimated to 109 Mm^3/year in 2016 (i.e., more than 290,000 m^3/day) [25]. In the Diass horst sensu strict (corresponding to the Sébikotane, Diass, Pout and Mbour compartments), pumping rate amounts are in the order of 85 Mm^3/year (i.e. 233,000 m^3/day) of which 156,000 m^3/day are used for the urban water for Dakar and Mbour. Pumping has increase continuously from 16,000 m^3/day in 1958 to 174,000 m^3/day in 2019 (Figure 4b). The total daily pumping rate is indeed quite higher than the maximum rate resulting from previous model [21] which was from 130,000 to 150,000 m^3/day in the Palaoecene and the Maastrichtian for study area of 4,350 km^2 [25].

3. Methodology

Piezometric and pumping data series were compiled from databases and technical reports from the Senegal Water and Sanitation Ministry (Direction de la Gestion et de la Planification des Ressources en Eau (DGPRE)) and Water Supply Companies (Société Nationale des Eaux du Sénégal (SONES), Sénégalaise Des Eaux (SDE), Office des Forages Ruraux (OFOR)). The data time series are nearly continuous since the 1960s but with short discontinuities. These data were completed within seasonal (dry and after rainy season) monitoring campaigns from 2007 to 2009, through 6 campaigns carried out on a network of 79 sampling points and from 2010 to 2019 at selected sampling points. Figure 5 show the water level monitoring network, location of pumping field, major faults and cross section (A, B, C) used for interpreting geological configuration.

During field campaigns, on site measurements relative to geographical position and depth to water table, were conducted at each location. Piezometric levels were computed using differential GPS measurements at the points. For wells tapping the Quaternary aquifers, elevations were deducted from the Digital Elevation Model (DEM) produced as part of this work with a precision of 6.5 m. This DEM was calculated with ASTER images (Advanced (Advanced Spaceborne Thermal Emission and Reflection Radiometer) by use of PCI Geomatica Orthoengine software for elevation extraction.

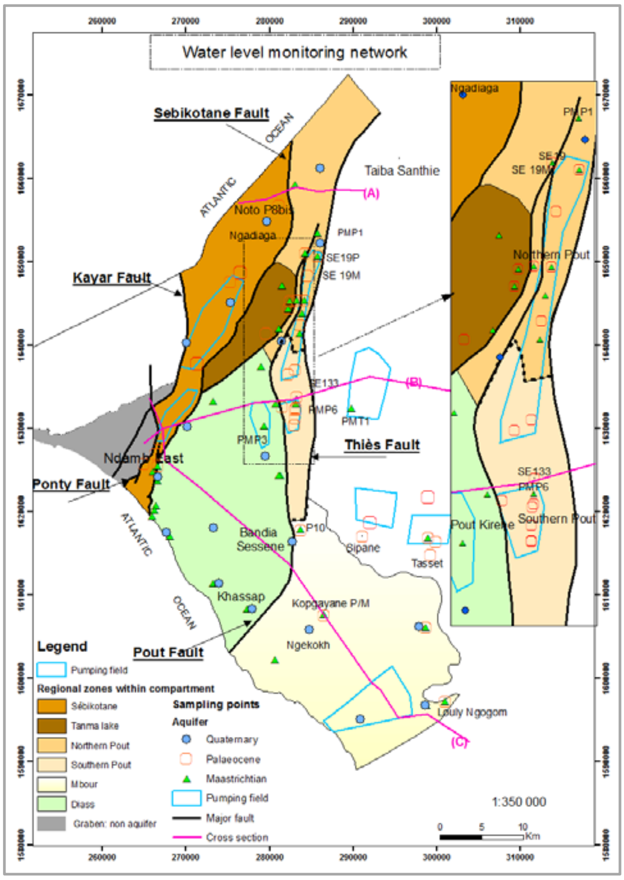


Figure 5. Water level monitoring network,location of pumping fields, major faults and cross sections (A, B, C) used for interpreting geological configuration

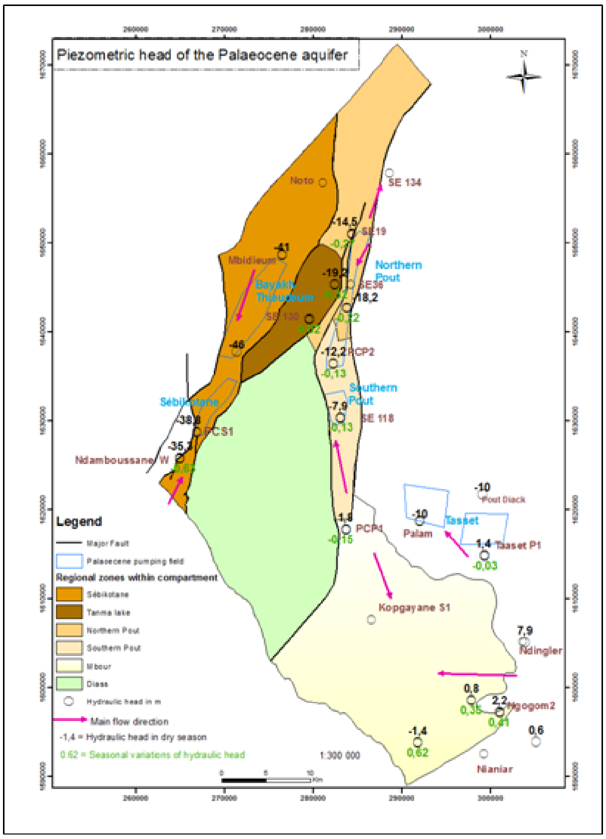
The impact of pumping on the aquifer system patterns and dynamics is studied by comparing the hydraulic head evolutions against urban drinking water pumping at the compartment scale, respectively in the Sébikotane, Northern Pout, Southern Pout, Mbour and Diass compartments (Figure 5). Most of piezometers are located close to this pumping field and variation of heads can valuably be interpreted with regards to pumping rates. Data used are monthly piezometric heads time series from the period 1960-1971 for wells located in the Northern Pout compartment and seasonal piezometric heads time series (measured before and after the rainy season) from 1971 to 2019 for most of the piezometers. Unfortunately, during this last period, the data are often incomplete. Indeed, the vertical groundwater flow exchanges are addressed using the geological configuration and the hydraulic head differences between aquifers in the same zone; lateral groundwater flow exchanges are also considered through the faults for the period 2019 were we have common data for the main aquifers; Palaoecene and Maastrichtian. For the superficial aquifer were current data are not available, we assume that the regime of 2009 still prevails because of very low pumping. The piezometric level is still higher than those of the two main aquifers and it is recharged by rainwater. The detailed geological configuration of the system has been updated using hydraulic and petroleum boreholes data, previous cross sections and geological map (1/50.000), and three geological cross sections have been drawn.

4. Results and discussions

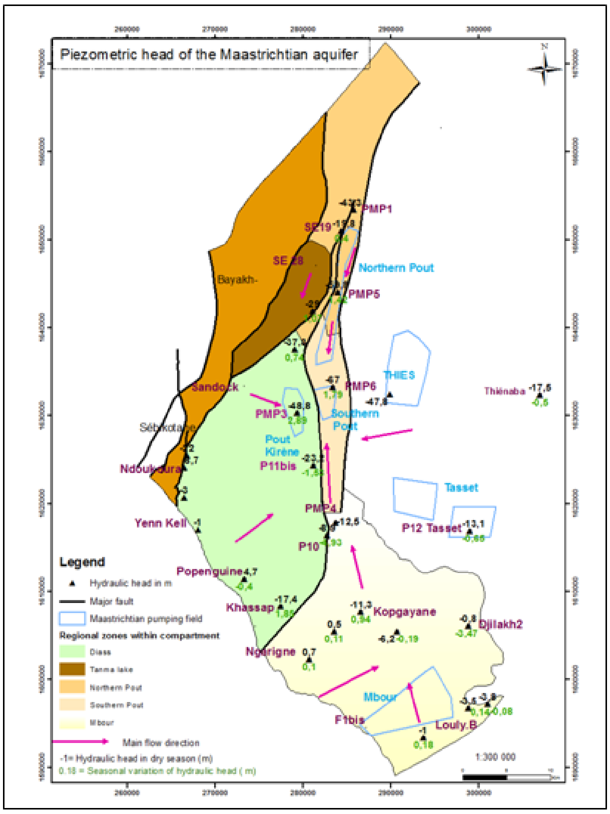
4.1. Main Groundwater Flow Pattern

The main flow directions are deduced from the hydraulic head data obtained in July 2019. The hydraulic heads in the Palaeocene aquifer range between +2.2 m to -46 m and the deduced groundwater flow is essentially directed towards the different pumping fields of Sebikotane, Northern and Southern Pout (Figure 6a, 6'a). For the Maastrichtian, hydraulic heads are between +4.7 m and -67 m and the groundwater flow is essentially directed towards the different pumping fields of Pout Kirène, Mbour, Northern and Southern Pout (Figure 6b, Figure 6'b).

Seasonal fluctuations between before (dry conditions) and after (wet conditions) the rainy season in the Palaeocene aquifer evidenced water level yearly decline rates in Sébikotane (-0.63 m) and in Pout compartments (-0.13 m to -0.32 m) while increasing in Mbour compartment between +0.35 to +0.62 m where the Palaeocene is unconfined under a thin Quaternary sands layer. In the Maastrichtian aquifer, decline of water level is observed in most of the samples with higher values in the range of -0.54 m, -0.65 m, -1.53 to -3.47 m respectively in Bandia, Tasset, Kirène, Djilakh, as a consequences of the high abstraction in these areas. However a rise of the water level between +0.1 m to +2.89 m is observed in Northern Pout (PMP5), Southern Pout (PMP6) and Diass (PMP3) compartments. These points are very close to boreholes and level can rise when there are not pumping. Also those former head correspond to local piezometric depressions that can allow convergent flow pattern. In Mbour compartment, the seasonal fluctuations may derive from recharge through the Palaeocene aquifer that is unconfined in this sector.

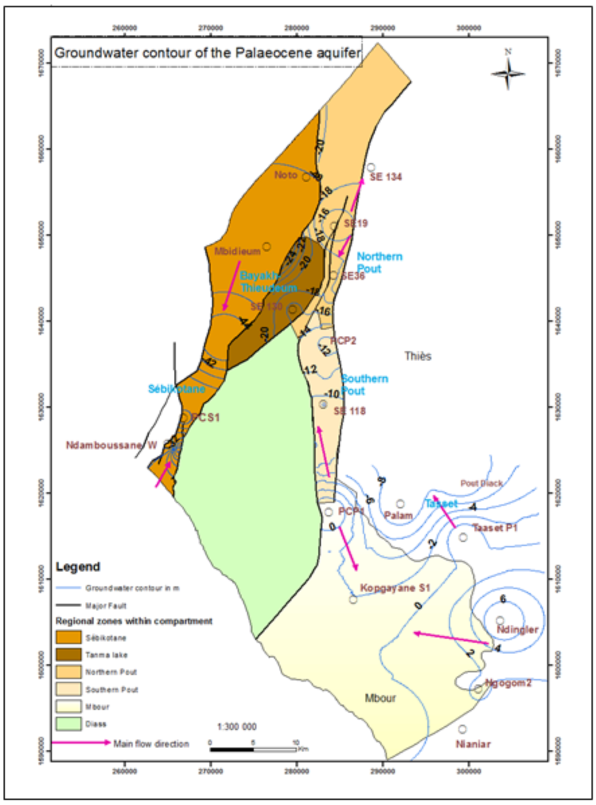


(a)



(b)

Figure 6. Piezometric heads and main groundwater flow directions in the Palaeocene (a) and Maastrichtian aquifers (b) in July 2019



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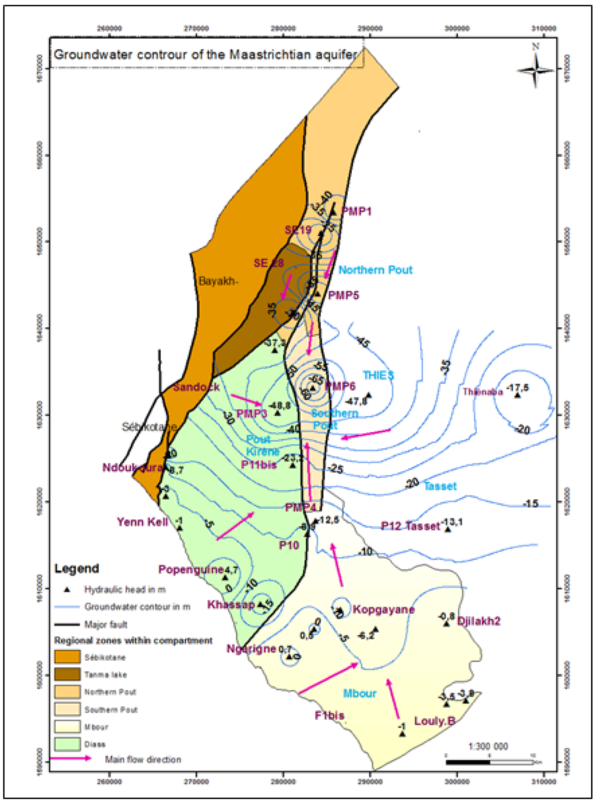

(b)

Figure 6'. Groundwater contour in the Palaeocene (a) and Maastrichtian aquifers (b) in July 2019

4.2. Hydrodynamic Behavior of the System under Exploitation

Given the spatial distribution of the piezometers in the aquifer system (Figure 5), head time series and pumping data are analyzed geographically at the compartments scale in the Sébikotane, Northern Pout, Southern Pout, Diass and Mbour areas (Figure 5). Monitoring wells in the system recorded (variably) long term groundwater levels since 1965. They feature groundwater depletion in all compartments and piezometric head is now below sea level except in the Palaeocene of Mbour (Figure 7f).

- In **the Sébikotane compartment** only the Palaeocene aquifer is exploited (Figure 7b), the Maastrichtian is made of clay. The general trend of groundwater levels shows clearly a lowering with slight seasonal fluctuations evidencing a recharge of the aquifer (Figure 7b). At the Damboussane West piezometer, the water level declines of 20 m with an average of 0.6 m/ year despite reduction of pumping rates. This trend started to slightly change to about 0.28 m/year from 2009 when pumping was reduced to less than 5,000 m^3/day.

- In the **Northern Pout compartment** (Figure 7c), groundwater abstraction began in 1978 in the Palaeocene and in 1984 in the Maastrichtian. The evolution of the groundwater level shows two major trends:

(1) from 1959 to 1971 prior to pumping, a steady state could be considered in the two aquifers and is marked by seasonal fluctuation of about 0.75 m/year in the Palaeocene and 1 m/year in the Maastrichtian aquifer (Figure 7c). The head value of the Maastrichtian were higher than those in the Palaeocene.

(2) from 1971 to 2019 a transient state is evidenced and a general decline is observed. The slight lowering from 1971 to 1975 before pumping started in that compartment maybe due to the impact from neighbor pumping in addition to climate effects. Three stress periods can be considered (Figure 7c):

- period from 1978 to 1983, when abstraction in the Palaeocene increased up to 25,000 m³/day resulting in an average head decline of approximately 0.57 m/year. The Maastrichtian aquifer (which was not yet exploited in this compartment) had still higher head values compared to the Palaeocene aquifer.
- period from 1984 to 1992, abstraction in the Maastrichtian started and increased from 8,700 m³/day to 35,600 m³/day and was lowered in the Palaeocene from 21,000 m³/day down to 14,800 m³/day. This induced first a greater drawdown of the heads in the Maastrichtian (0.51m/year) then equilibrium with the Palaeocene (Figure7c) where the decline is 0.51 m/year.
- period from 1993 to 2019 which corresponds to higher abstraction rates in the Maastrichtian (35,000 m³/day) and lower pumping in the Palaeocene (from 14,800 to 8,000 m³/day) exhibit a reversal of the hydraulic gradient between the two aquifers with now higher heads in the Palaeocene then in the Maastrichtian aquifer.

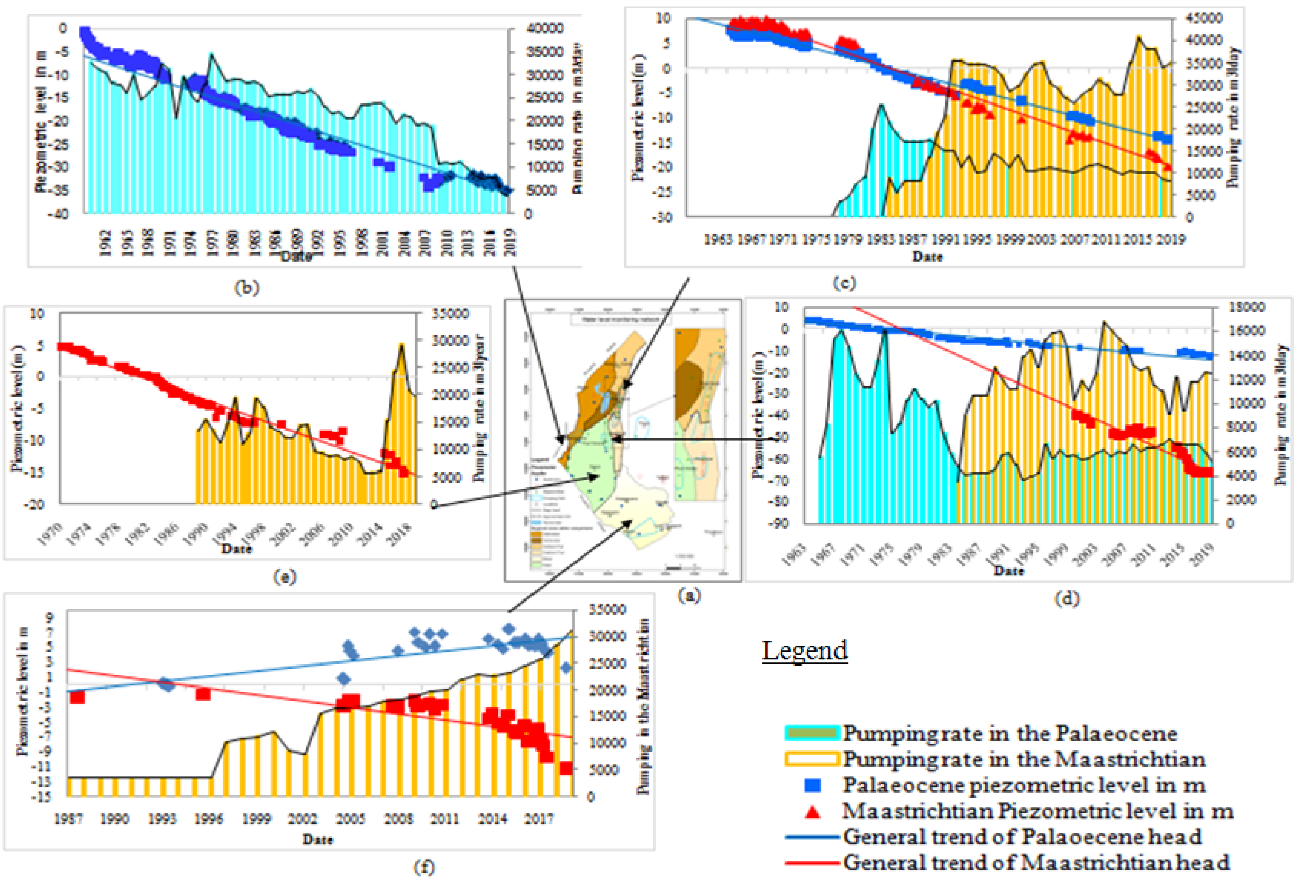

Figure 7. Spatial distribution of the groundwater level monitoring network (a), evolution in time of the measured piezometric head with pumping rate in Sebikotane (b), Northern Pout (c), Southern Pout (d), Diass (e) and Mbour areas (f)

- In the **Southern Pout compartment** (Figure 7d), abstraction in the Palaeocene began in 1965 and increased from 5,500 to 16,000 m^3/day in 1974 inducing a great head decline of 0.52 m/year. They were progressively reduced to 5,000 m^3/day in 2019. These pumping rates impacted continuously the Palaeocene aquifer (at SE133) with a mean drawdown of 0.3 m/year between 1964 and 2019. The Maastrichtian aquifer (PMP6) shows a drawdown with different patterns. The water level is lower than in the Palaoecene and seems to show the effect of the pumping rate trends that increases from 3,500 (in 1984) to 12,500 m^3/day (in 2019).

- In the **Diass compartment (**Figure 7e**),** where the Maastrichtian aquifer outcrops (the Palaeocene does not exist) the pumping began in 1989 and has evolved at different regime. Groundwater level records in Bandia (P10) show a continuous head decline of about 0.42 m/year between 1971 and 2018. The latter increases to 1.04 m/year since 2014 corresponding to a dramatic increase of pumping rate from 6,000 to 20,000 m^3/day in 2019.

- In the **Mbour compartment** located in the South (Figure 7f), the Maastrichtian aquifer evidenced a head level below that of the overlying Palaeocene since 1988 and an average head decline of 0.31 m/year in Kopgayane piezometer. This is mainly due to increase pumping from 3,500 to 30,000 m^3/day where as water level in the Palaeocene is variable. In this part of the system, the Palaeocene is outcropping and is poorly exploited because of relic saline waters from the last marine transgression.

The spatial and temporal analysis of the piezometric heads indicates that the influence of pumping is predominant on the groundwater flow patterns in the aquifer compartments, showing indeed a general decline with increase of pumping. Although other factors such as the effective direct recharge, the vertical or lateral leakage can have an impact on these fluctuations.

Many studies [10,11,13,15] (among others) have evidenced that high water abstraction has caused a continuous groundwater level decline, and consequently important modification of the groundwater flow pattern and deterioration of groundwater quality through salinization.

4.3. Interpretation in Terms of Groundwater Flow Exchange and Conceptual Model

4.3.1. Groundwater flow exchange

In this section, we will discuss possible vertical and lateral groundwater flow exchanges through faults using primarily geological information and heads differences from data collected in 2019 (which corresponds to the more complete data set). In this prospect, three hydrogeological cross sections and groundwater head level records from both sides of each major fault of Ponty, Sébikotane, Pout and Thiès (Figure 5, Figure 9) are used to define the conceptual system (Figure 8).

- Role of Ponty Fault

In the western part of the system, the Ponty fault (Figure 8 cross section B and C) is an low permeability fault between the clayey Palaeocene and Maastrichtian to the West and the Sébikotane Palaeocene compartment in the East. It is the same for the shallow aquifer in the southern part of the system where Eocene clays are outcropping in the Rufisque graben (Figure 5).

- Role of the Sébikotane fault

The groundwater flow exchange through this fault is studied from the hydrogeological cross sections A and B. The cross section A of Figure 8 shows a contact between the Palaeocene aquifer of the Sébikotane compartment (West of the Sébikotane fault) and the Maastrichtian aquifer of the Northern Pout (between Sébikotane and Thiès faults) compartment. However, when considering the large head difference between the Palaeocene of Sébikotane and that of Northern Pout (Figure 9a) and the geological structure (Figure 8 section A) we can deduce that this fault is a low permeability. It is the same between the Palaeocene of the Sébikotane compartment and the Maastrichtian of the Diass (between Sébikotane and Pout faults) compartment. This latter is clayey at the West of the Paki fault (Figure 8 section B). Piezometric head differences (Figure 9b) confirm that this fault has a low permeability.

- Role of the Pout fault

The groundwater flow exchanges through the **Pout fault** are studied from the hydrogeological cross sections B and C (Figure 8). This fault put in contact the sandy Diass Maastrichtian aquifer in the West with the karstic Palaeocene and Maastrichtian aquifers of Southern Pout in the East (between the Pout and Thiès faults) (Figure 8, cross section B). The differences in piezometric heads between these two aquifers from 1962 to 2009 (Figure 9c, d) reflects a groundwater flow from West to East. But since 2014 when pumping increased in the Maastrichtian from 6,000 to 20,000 m^3/day in 2019 while they were maintained at a relatively low level in the Palaeocene (between 6,000 and 5,000 m^3/day from 2009 to 2019) as mentioned in section 4.2, groundwater flow is reversed (Figure 9c) from East to West. However, the difference in Maastrichtian heads values (Figure 9d) reflects that the groundwater flow still from West to East.

The cross section C in Figure 8 shows the lateral contact between the Maastrichtian aquifer of the Diass compartment in the West and the Palaeocene and Maastrichtian of Mbour compartment in the East (East of the Pout fault). In 2009, the slight differences in piezometric heads allowed a West to East groundwater flow. However since 2015 piezometric heads in the Maastrichtian on both side of the fault (Figure 9e**)** invoke an East-West groundwater flow direction (Figure 8**)** probably due to high abstraction for intensive agri-business and industrial activities that are well developed in this area.

- Role of the Thiès fault

To the East of this **Thiès** fault, the Palaeocene is not aquifer because of compact and low permeability limestone. The highest hydraulic heads of the Maastrichtian at the East of the fault (Figure 9f, g) suggests that the groundwater flow would be from the East towards the horst.

4.3.2. Conceptual Scheme of the Flow Pattern in the System

The piezometric head differences between both aquifers occurring from 1980 suggest a downward groundwater flow from the Palaoecene aquifer recharging the

Maastrichtian aquifer (Figure 7c, d, f, Figure 9a, e) through the marly calcareous lower Palaeocene aquitard (Figure 8 cross sections A, B, C**)**. However, in the part that is confined by the clayey Eocene, the Palaeocene would likely be locally recharged from the Ndoyène and Pout fossil valleys and the superficial aquifer in the unconfined parts (Figure 8 cross sections A, B, C). Derived from the previous considerations and globally, three major types of groundwater flow patterns can be distinguished in this complex hydrogeological system.

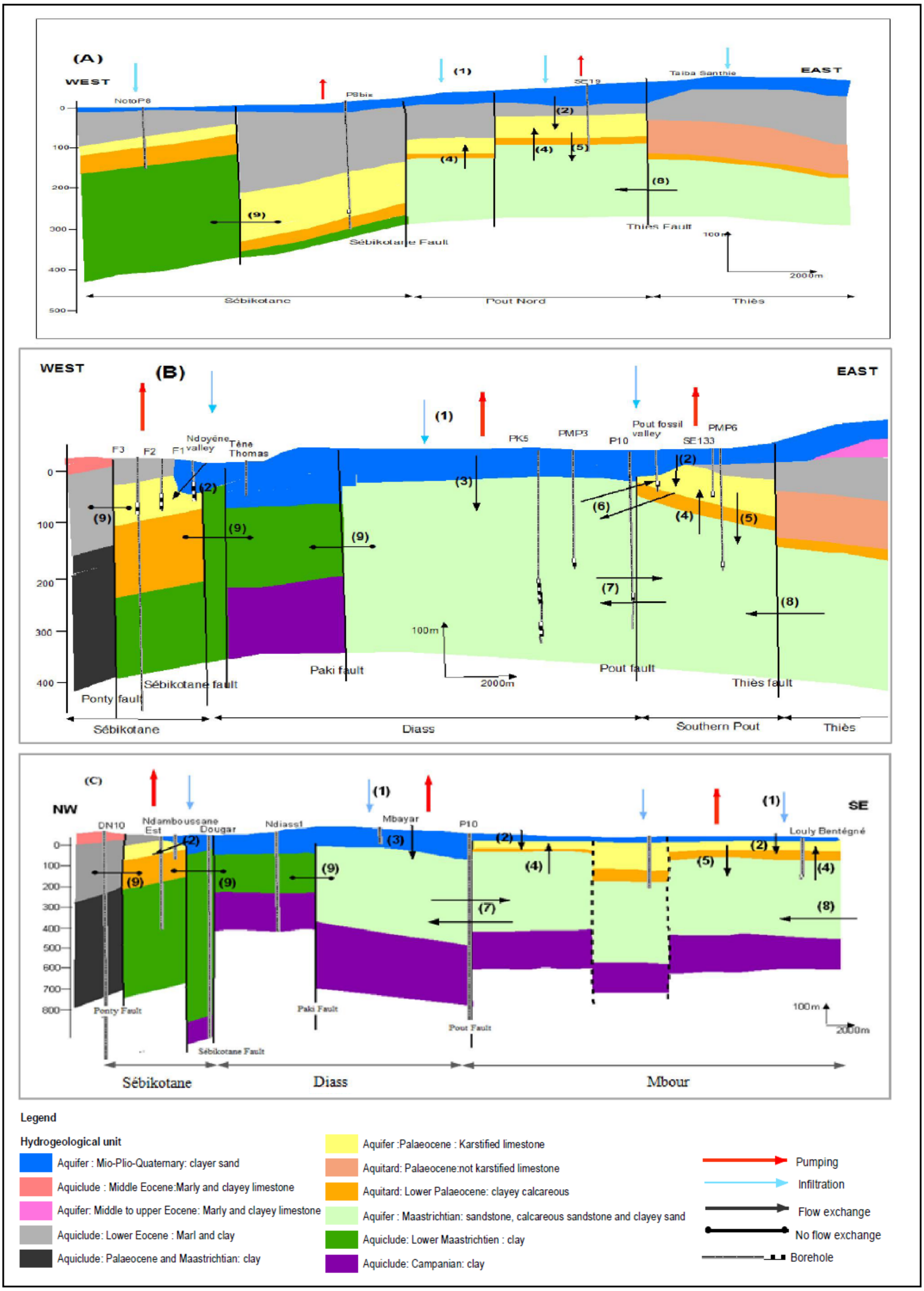

Figure 8. Conceptual scheme of the groundwater flow patterns in the horst aquifer system

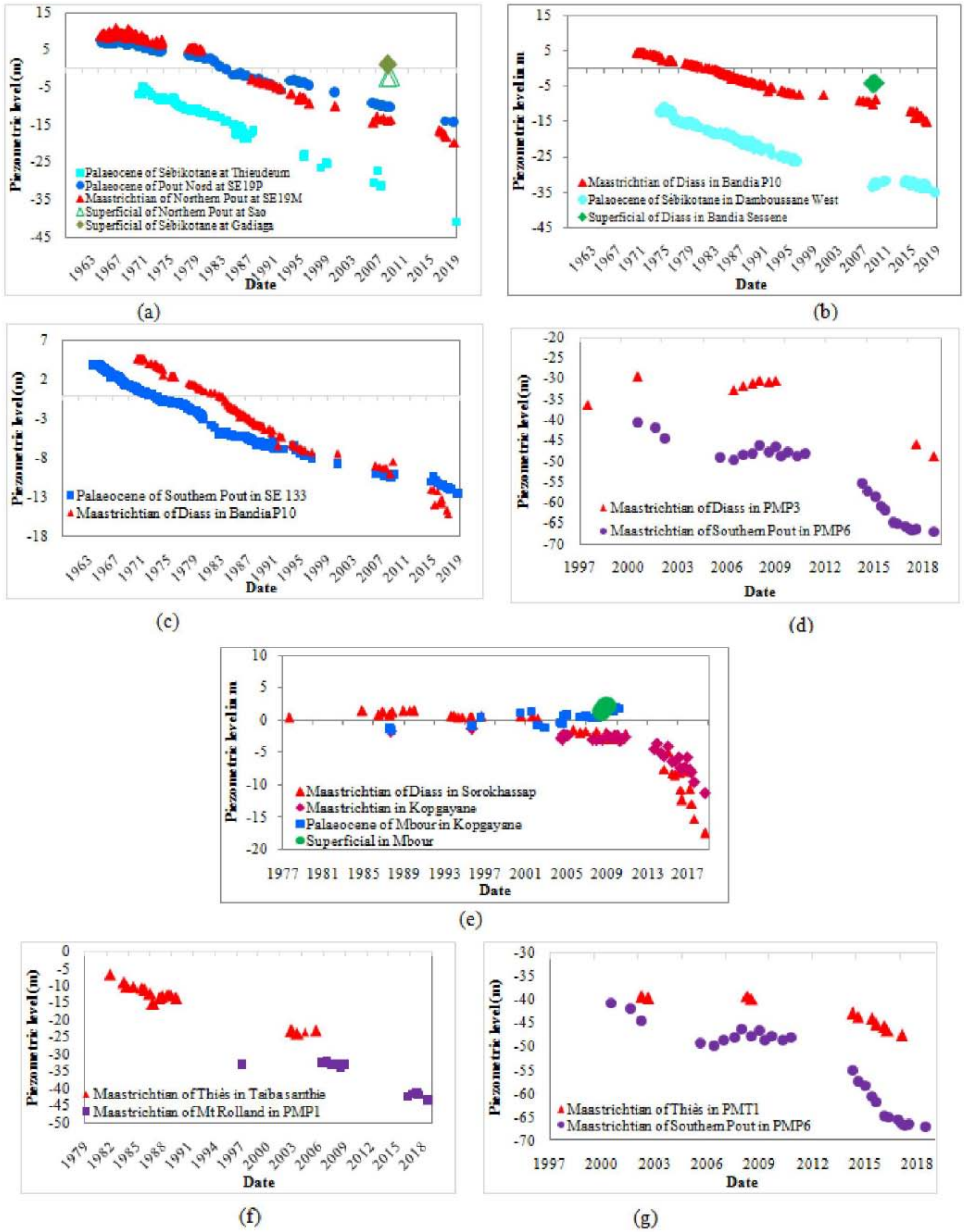

Figure 9. Evolution of the piezometric level on both sides of the faults: **Sébikotane fault** between the Sébikotane and Nothern Pout compartments (a) and between Sébikotane and Diass compartments (b) **Pout fault** between the Maastrichtian of Diass and the Palaeocene of Southern Pout (c), the Maastrichtian of Diass and that of Southern Pout (d), the Maastrichtian of Diass and the Paleocene of Mbour and the Maastrichtian of Diass and that of Mbour (e); **Thies fault** in the North (f) and South of the system (g)

1) Direct infiltration and vertical flow exchange

Vertical infiltration of rainwater and vertical exchanges between aquifers occur in the following conditions:

(1) direct infiltration of rainwater in the Quaternary aquifer;

(2) downwards vertical leakage from the Quaternary aquifer to the Palaeocene aquifer in the Mbour-Pout compartment;

(3) downwards vertical leakage from the Quaternary aquifer to the Maastrichtian aquifer in the Diass area;

(4) upwards vertical leakage from the Maastrichtian aquifer to the Palaeocene limestone aquifer prior to 1980s;

(5) downwards vertical leakage from the Palaeocene limestone aquifer to the Maastrichtian aquifer in the Mbour-Pout compartment post 1980s.

2) Lateral groundwater flow patterns

Horizontal groundwater flow exchanges through the faults occur in the following conditions:

(6) lateral flow from the Diass Maastrichtian aquifer to the Palaeocene aquifer of the Southern Pout compartment prior to 2009 and reversed groundwater flow after 2009. This situation may change depending to pumping regime.

(7) hydraulic continuity in the Maastrichtian aquifer: lateral flow occurs from the Maastrichtian aquifer of the Diass compartment in the West to the Maastrichtian of Mbour compartment in the East prior 2009 and reversed groundwater flow from East to West after 2009. This situation may change depending to pumping regime.

3) regional groundwater flow within the Maastrichtian aquifer

Changes in the regional groundwater flow within the Maastrichtian aquifer occur:

(8) to the eastern limit of the horst system, the groundwater flow in the Maastrichtian aquifer is directed from East to the West since the piezometric gradient has been reversed.

(9) no flow exchanged through the Ponty, Sébikotane and Paki faults.

4.4. Groundwater Flow Regime

Records of hydraulic head since 1965 exhibit a groundwater depletion in both aquifers (Figures 7 and 9) and show two types of evolution: seasonal variations (on an annual basis) related to seasonal recharge and long term piezometric level evolution (interannual variations) which reveals two periods of groundwater regime (Figure 10a).

- A steady state period from 1965 to 1971 with similar seasonal variations indicates recharge (Figure 10a (I)) in both aquifers. During this period, only the Palaeocene aquifer was really exploited (Figure 10b (I)) and the measured heads are slightly lower than the Maastrichtian heads (Figure 10a (I)).

- A transient period from 1971 to the present day is characterized by a generalized and continuous decline of the piezometric heads (Figure 10a (II)). With regards to the pumping regime and head change patterns, three stress periods can be distinguished.

○ **A first stress period,** which spans from 1971 to 1983, the groundwater regime is characterized by a decline of the piezometric heads in both aquifers. This is likely also the result of a decrease in rainfall (-37% from 1938 to 1983) started in 1970 and an increase of the pumping in the Palaeocene aquifer while relatively low and steady in the Maastrichtian aquifer (Figure 10b (II, 1)). During this period, the head in the Maastrichtian aquifer is higher and seasonal fluctuations still occurred (Figure 10a (II, 1)) but muted by pumping effects.

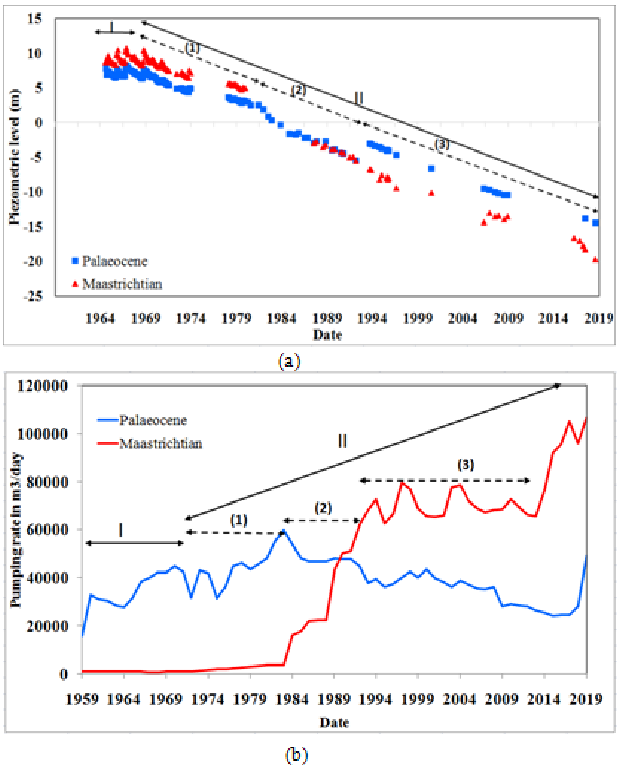

Figure 10. Evolution of the piezometric heads with pumping from 1959 to 2019 (a) Evolution of piezometric heads with time; (b) evolution of pumping rate with time: I = Steady state period, II = Transient period (1) (2) (3) are respectively considered as stress periods 1, 2 and 3 of the transient period

○ **A second stress period,** which spans from 1984 to 1992, corresponds to an increase of pumping in the Maastrichtian aquifer and a decrease in the Palaeocene aquifer (Figure 10b (II, 2)); the piezometric heads in both aquifers are relatively in equilibrium (Figure 10a (II, 2)) but continue to decrease.

○ **A third stress period**, which spans from 1993 to the present days, with pumping from the Maastrichtian aquifer being almost constant and maintained at a high level until 2013 while it is reduced in the Palaeocene aquifer before increasing from 2014 (Figure 10b (II, 3)). The general drawdown of the groundwater level has increased and an inversion of the hydraulic gradient between the two aquifers occurred; here, the Maastrichtian aquifer heads became lower than the piezometric heads in the Palaeocene aquifer (Figure 10a (II, 3)). Since 2014 in order to solve deficit in drinking water for Dakar, pumping are increased in both aquifers mainly in the Maastrichtian.

5. Conclusions

The Diass horst aquifer system is highly exploited for drinking water, added to industrial and agricultural uses in the Sébikotane, Diass, Pout and Mbour compartments with a global pumping rate in the order of 85 Mm^3/year (i.e. 233,000 m^3/day) of which 156,000 m^3/day are pumped as drinking water for Dakar and Mbour. Pumping increases continuously from 16,000 m^3/day in 1958 to 174,000 m^3/day in 2019 distributed over the pumping fields in Sébikotane, Bayakh, Thieudeum, Diass, Northern Pout, Southern Pout, Mbour, Thiès and Tasset. Those high pumping rates influence considerably the main groundwater flow direction towards the pumping fields and have caused a continuous and generalized piezometric head decline mostly pronounced in the Palaoecene of Sébikotane (0.6 m/year from 1958 to 2009 and decreased to about 0.28 m/year from 2009 when pumping was reduced to less than 5,000 m^3/day) and in the Maastrichtian of Northern Pout compartment (0.57 m/year from 1971 to 2019). The Maastrichtian aquifer in the Diass compartment shows a continuous decline of about 0.42 m/year (1971 and 2018) and 0.31 m/year (1988 to 2019) in the Mbour compartment.

Undoubtedly, spatial and temporal head changes are due to the high pumping regime, although other factors such as the direct recharge, vertical or lateral leakage can have an impact on the head fluctuations. The conceptual scheme derived from this spatio-temporal analysis in relation to the geometric and structural configuration of the aquifers shows that the reservoir acts as a multilayer aquifer system with interconnected compartments subdivided by faults that allow groundwater flux exchanges except the low permeability Ponty and Sébikotane faults. The groundwater flow regime shows two distinct periods: a steady state period from 1965 to 1971 where the Maastrichtian aquifer has higher piezometric heads compared to the piezometric heads in the Palaeocene aquifer that was already exploited; a transient period from 1971 to the present days characterized by a generalized and continuous decline of the piezometric heads due to pumping increase mainly in the Maastrichtian aquifer. This latter induces from the year 1980 a modification of the groundwater flow corresponding to an inversion of the piezometric gradient between both aquifers (i.e. the Palaeocene aquifer has higher piezometric heads compared to those of the Maastrichtian aquifer). Currently, the conceptual model of the groundwater flow can be described as following: the Quaternary superficial aquifer is vertically drained by the deeper aquifers of the Palaeocene and Maastrichtian (1), this latter draining the Palaeocene aquifer (2), lateral groundwater flow occurs from the Diass Maastrichtian to the Pout Sud and Mbour compartment or vice versa according to the pumping and inversely from the Thiès Maastrichtian to the Pout compartment through the Pout and Thiès faults respectively (3); no flow exchange occurs through the Ponty and Sébikotane faults except in the Ndoyène valley (4).

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