IMPACT OF THE PUMPING REGIME ON THE RECHARGE BALANCE OF THE CONTINENTAL TERMINAL AQUIFER OF THE ALLADA PLATEAU: CASE OF THE GODOMEY AND OUÉDO WELLFIELDS IN THE COMMUNE OF ABOMEY-CALAVI (SOUTH BENIN).

Abstract:

The Continental Terminal aquifer is the main hydrogeological formation exploited for the supply of drinking water to the populations of southern Benin. This study evaluates the impact of the intensive pumping regime of the Ouèdo and Godomey wellfields on the recharge of the Continental Terminal in the Municipality of Abomey-Calavi. The methodological approach is based on a comparative analysis of pumping tests (2001-2023) using the OUAIP software, a modelling of natural recharge over the period 2011-2025 using the ESPERE tool (Water Table Fluctuation and Turkish methods) using an effective porosity of 0.26, as well as a statistical forecast estimate based on linear regression line equations cross-referencing the demographic evolution of the INSTAD and the historical of SONEB levies. The results show a decrease in the values of the hydrodynamic properties of the Continental Terminal under the effect of intensive pumping. Indeed, the average transmissivity has dropped from $7.97.10^{-3} m^2/s$ in 2001 to $2.22.\ .10^{-3} m^2/$ s in 2023. At the same time, the storage coefficient increased from $.10^{-9}$ in 2001 to $2.33.\ 10^{-3}$ in 2023, reflecting a localized deconfinement and a shift from captive to semi-captive or free behavior. The Godomey wellfield alone is undergoing an average intensive extraction rate of 47,000 m³ per day, bringing annual withdrawals to 34 million m³ for a population served that already reaches 1.3 million inhabitants in 2025. The application of the equations of regression lines shows a strict linear correlation between population growth and the artificial discharge of the water table. Mathematical projections for 2040 establish that the population will reach a critical 1.95 million inhabitants, propelling the need for drinking water and the volumes withdrawn from the Godomey field to an estimated level of 58.3 million m³/year. Faced with the threat of widespread drying up, regulation of operating flows coupled with urgent artificial recharge actions is essential.

Keywords: Continental Terminal, Evolution, Wellfield, Benin, Overexploitation

Introduction:

The effectiveness of life on earth, whether animal, plant or human, results from the availability of water resources for one or other species. Its primordial and sacred character is why it is called blue gold. Although it is largely available on land, a proportion of 71% of hydrosphere compared to 29% of the continent, it is still unusable for most of its vital needs (drinking water, water for domestic needs, water for agricultural needs, etc.). (Shiklomanov, 1993) Indeed, 97.2% of the available water represents the waters of the oceans and seas which have a high salinity, thus making the resource unexploitable for vital needs. Only 2.8% of this resource is freshwater, divided into glaciers and ice caps (2.15%), groundwater (0.62%) and surface water (0.03%) (CIEAU, 2019). These statistics illustrate the scarcity of the resource, although it seems to be available. Thus, the water most suitable for daily needs, particularly for consumption as a primary need, is groundwater, which represents 0.76% of the body of water available in the world for a total of 8.3 billion inhabitants worldwide. These figures call into question the need for rational management of the resource with a view to its preservation and sustainability for future generations, as stipulated in the first principle of IWRM: Fresh water is essential for life, development and the environment. Its management must be sustainable to preserve ecosystems. One wonders whether the current pumping regime induces overexploitation or an imbalance in the water balance? It is thus in continuity with previous studies in hydrology and the increasing rate of groundwater exploitation that we have been interested in the Impact of the pumping regime on the recharge balance of the aquifer of the Continental Terminal of the Allada Plateau: the case of the Godomey and Ouèdo wellfields in the commune of Abomey-Calavi (South – Benin). This study will allow us to assess the impact of groundwater exploitation on natural recharge by comparing the hydrodynamic data of the aquifer that has been exploited for years with the responses to today's demands in order to make a projection into the future and propose concrete solutions to preserve the resource.

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The general objective of this study is to evaluate the impact of the pumping regime of the Godomey and Ouèdo wellfields on the recharge of the Continental Terminal aquifer of the Coastal Sedimentary Basin in southern Benin.

To achieve this overall goal, we have defined the following specific goals:

- Assessing the hydrodynamic functioning of the Continental Terminal aquifer from 2001 to 2025
- Estimate the annual recharge balance of the aquifer over the period from 2011 to 2025
- To assess the temporal evolution of water needs and population growth served by the Godomey and Ouèdo wellfields over the period from 2011 to 2025.

In order to orient the investigations and answer the questions raised by the previously defined objectives, the following research hypotheses are formulated:

- The Continental Terminal aquifer in the municipality of Abomey-Calavi would have a high transmissivity, but would be subject to intense stress, thus reducing its performance over time;
- The natural recharge of the aquifer would become insufficient to compensate for the annual withdrawals and would be rapidly discharged, due in particular to the intensive exploitation of the resource;
- Population pressure and the demand for water needs are the basis of the rate of extraction of the aquifer, which tends to exceed the annual recharge capacity of the aquifer

The study context

The Commune of Abomey-Calavi is located in the Atlantic Department of the Republic of Benin. It lies between the parallels 6°22' and 6°30' north latitude and the meridians 2°15' and 2°22' east longitude. It is bordered to the north by the commune of Zè, to the south by the Atlantic Ocean, to the east by the communes of Cotonou and So-Ava and to the west by the communes of Ouidah and Tori-Bossito. It covers an area of 539 km2; nearly 20% of the area of the department and 0.47% of the national area and has a population that is estimated at 656,358 inhabitants in 2013 with 332,784 women and 323,574 men. The commune has nine (9) arrondissements: Abomey-Calavi; Akassato; Godomey; Golo-Djigbé ; Hèvié; Kpanroun; Ouèdo; Togba and Zinvié and One hundred and forty-nine (149) villages and city districts. (RGPH 4, 2013). Given the proximity of the municipality of Abomey-Calavi to the municipality of Cotonou, it represents a very dynamic region and is popular with the population. Figure 3 illustrates the geographical location of the municipality of Abomey Calavi.

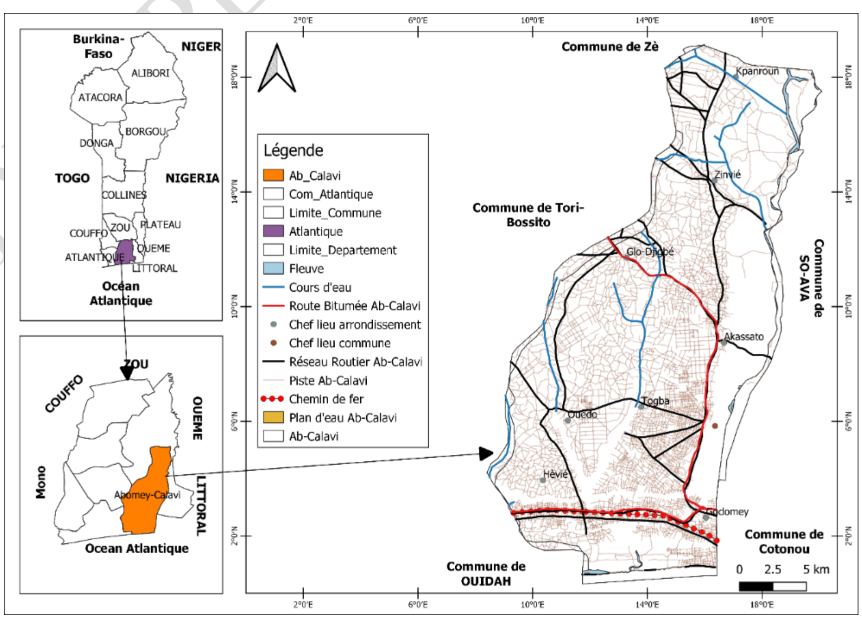

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Figure 3 : Geographical map of the municipality of Abomey-Calavi Source: IGN 2018 topographic collection

Géomorphologie

La géomorphologie de la commune d'Abomey-Calavi révèle un relief peu accidenté. Les principaux traits caractéristiques de ce relief sont : une plaine faite d'une bande sablonneuse avec des cordons littoraux récents et anciens ; un plateau de terre de barre séparé de la plaine par la rivière Djonou et le lac Nokoué ; des dépressions et des marécages dans les zones situées sur la berge du lac et de la lagune (Monographie départementale, 2019). La plaine côtière présente des terrains à perméabilité élevée, ce qui favorise une infiltration rapide des eaux de pluie et par conséquent une pollution assez rapide de la nappe phréatique avec un faible pouvoir de filtration des éléments véhiculés par l'eau. Les terrains constituant la terre de barre quant à eux ont une porosité assez faible, ce qui rend leur perméabilité moins prononcée que celle des formations de la plaine côtière. La figure 5 ci-dessous présente la carte géomorphologique de la commune d'Abomey-Calavi.

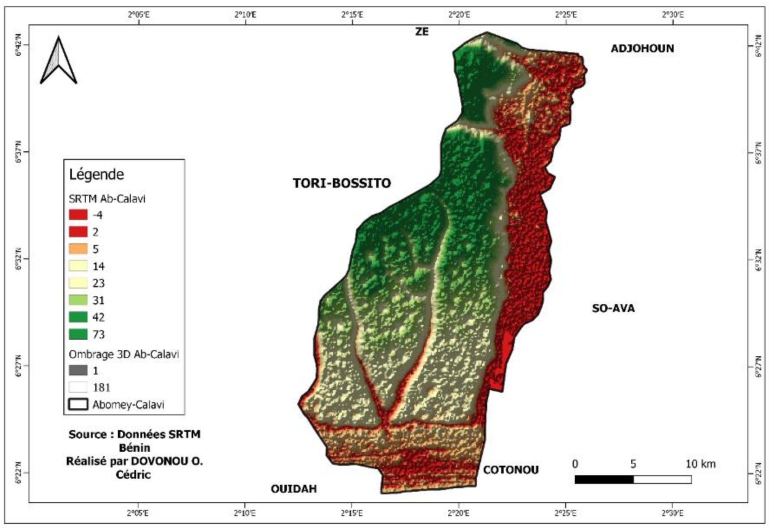

Figure 1: Carte géomorphologique de la commune d'Abomey-Calavi ; Source : Données SRTMBénin

Hydrographie

Le réseau hydrographique est constitué essentiellement de deux plans d'eau que sont le lac Nokoué et la rivière Djonou. Par ailleurs, la commune dispose d'une façade maritime juxtaposée à la lagune côtière (lagune de Togbin), de marais, de ruisseaux et de marécages. La figure 6 présente le réseau hydrographique de la commune d'Abomey-Calavi et de ses environs.

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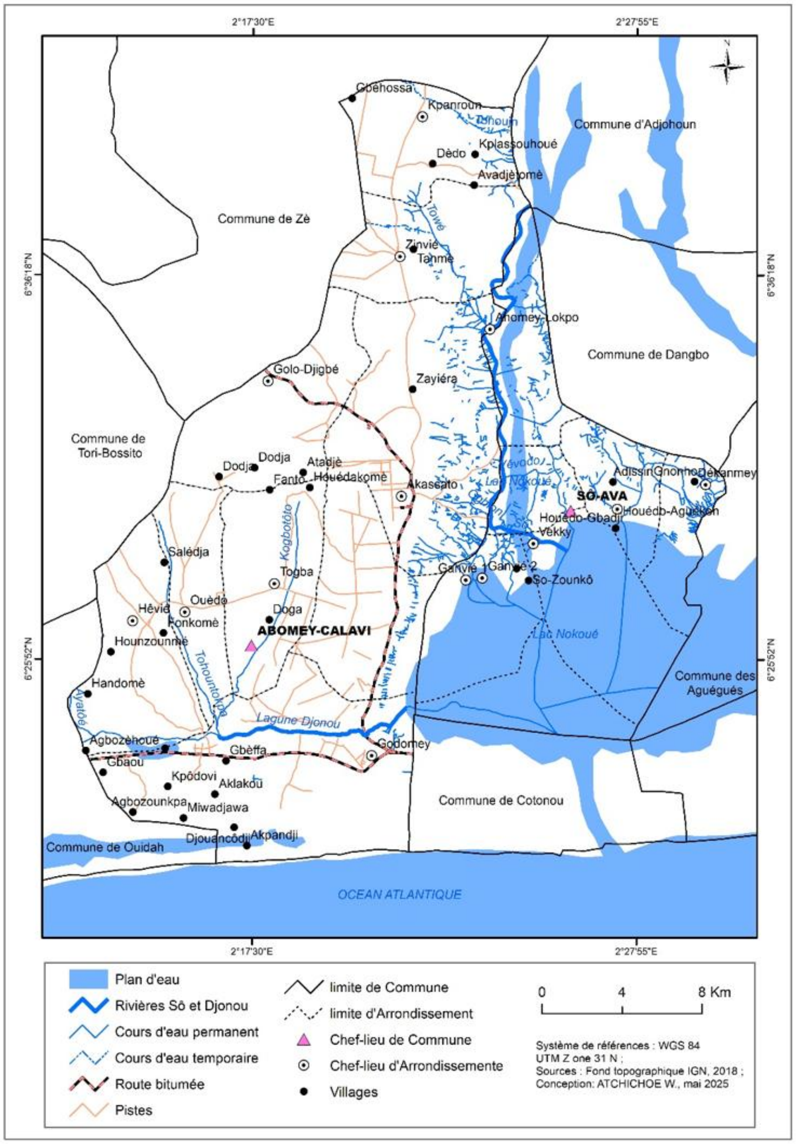

Figure 2: Carte hydrographique de la Commune d'Abomey-Calavi et de ses environs Source : Thèse de doctorat, ATCHICHOE W., mai 2025

Materials

In order to carry out this work, we have used a state-of-the-art computer tool with data processing software in accordance with our needs and the objectives set before our work. It is a laptop from the HP Elitebook × 360 830 G6 with a storage capacity of 250 gigabytes for the storage of the data we have collected; Excel 2019 software for statistical data processing; Word 2019 for word processing; QGIS Desktop 3.10.8 with GRASS 7.8.3 for the creation of the maps; the ESPERE software for the estimation of recharge using several implemented methods;

OUAIP_v3.1-R13 software for the processing and interpretation of pumping test data and digital terrain models and shapefiles, raster for the complete production of maps and the extraction of altitudes. In addition to all this computer equipment, we have collected data from various structures, the processing and interpretation of which has enabled us to achieve the objectives we have set ourselves.

Methods

- **Literature search**

The first step was to conduct a well-structured literature search that allowed us to contextualize our work, take stock of the review and the work already done in order to clearly define our objectives and guide our research. We have therefore consulted and exploited old dissertations as well as articles, publications, theses whose themes are related to ours. We went to the Benin Excellence library of the Valley Foundation and the library of the National Water Institute to appropriate the physical documents and we consulted the online documentation on the various scientific sites. All of this documentation has enabled us to have data relating to the geographical location, hydrography, pedology, geology, hydrogeology, geomorphology of our study area as well as the chronicle of SONEB production data and demographic data.

- **Data Collection**

This step follows the documentary research that we had described above. Thus, we went to the competent structures to collect data and technical information on our study area. To this end, we went to the Departmental Directorate of Energy, Water and Mines of the Atlantic- Littoral (DDEEM Atl-Lit) as well as to the General Directorate of Water, the National Water Company of Benin (SONEB), the International Institute of Tropical Agriculture (IITA) in order to collect the following information:

Data from long-term and short-term pumping tests carried out in the Municipality of Abomey-Calavi (data obtained at the DDEEM Atl-Lit);

Data from pumping tests (long and short-term) carried out in 2001 during the drilling of certain boreholes in the wellfield;

Monitoring data from the piezometers of the Ouèdo and Godomey wellfields (data obtained from SONEB and the General Directorate of Water);

Climate data for the period 2011 to 2025 (data obtained from IATI);

Operating data of the boreholes of the Godomey and Ouèdo wellfields (operating flows, geographical coordinates of the various boreholes);

Data on the annual volume of water pumped from the Godomey wellfields over the period from 2011 to 2025 (data obtained from SONEB).

- **Data processing**

The processing of the data obtained and collected was carried out according to the objectives we set ourselves. We therefore started from the estimation of productivity, then from the determination of the specific flow, the transmissivity of the aquifer, the simple drawdown and the specific drawdown for specific objective 1 which is to characterize the hydrodynamic functioning of the aquifer using data from long and short pumping tests carried out in the Municipality of Abomey-Calavi. As for specific objective 2, which is to estimate the recharge balance of the aquifer using the Turc method and the piezometric level fluctuation method, we have described and processed each of the necessary data, in particular climatological data and piezometric level monitoring data collected on the Godomey and Ouèdo wellfields. Finally, in order to meet specific objective 3 relating to the study of the annual volume of water pumped, the population growth of the populations served by the Godomey and Ouèdo fields and the population, we produced the table of annual variation in water needs represented by the volume of water pumped over time as well as the evolution of the population to correlate this demographic increase with the exploitation of the resource. The following paragraphs describe the methodology adopted for each step.

- **Productivity estimation**

The productivity of an aquifer is the ability of the aquifer to provide a minimum exploitable flow through the channel of a catchment structure (Gombert, 1997). For a better assessment of borehole flows, the Inter-African Committee for Hydraulic Studies (C.I.E.H) has proposed the following classification (Lams et al, 2000)

Table 1: Assessment of the operating flows of a hydrogeological structure (Lams et al, 2000)

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Flow rates	**Assessment**
0 – 1 m3/hr	Very Low
1 – 2.5 m3/h	Low
2.5 – 5 m3/h	Medium
>5 m3/hr	Strong

As for the transmissivity, it was calculated by the Theis method with the drawdown data of the structures available during and after the pumping stopped during the ascent. The following classification allows for an analysis of transmissivity (Lams et al, 2000)

Table 2: Assessment of the transmissivity of an aquifer

Transmissivity	**Assessment**
T < $^{10-5}$ m2/s	Low
$^{10-5}$ m2/s < T < 10-4 m2/s	Medium
T > $^{10-4}$ m2/s	Strong

- **Determination of the specific flow rate**

The characteristics of a structure and its immediate perimeter are determined using pumping tests carried out in the environment. These pumping tests make it possible to estimate the critical flow, the relative specific flow, the critical flow of the structure, and the different pressure drops subjected to pumping. To determine these different parameters, we had several stepwise pumping data. The specific flow parameter (ratio between flow and drawdown) is calculated from the flow values of the first stage and those of the drawdown s (m). We limited ourselves to the first level to reduce the influence of square pressure losses at the pumping structures. The mathematical writing of this flow rate is defined by: $Qs = \frac{Q}{s}$

(1)

Qs : specific flow rate in (m2/h) Q: pumping flow rate in (m3/h): drawdown

- **Determination of transmissivity**

Transmissivity is a fundamental hydrodynamic property that measures the ability of an aquifer to transmit water through its full saturated thickness. It expresses the flow of water that flows per unit width of the aquifer under the effect of a unit hydraulic gradient (Castany et al, 1982). We based ourselves on data from a borehole carried out with a long-term pumping test. To process these data successfully, we used the Test Pumping Interpretation Tool (OUAIP software) which allowed us to interpret the long-term and short-term pumping test data using the Theis method. Indeed, the OUAIP software is a tool developed and distributed free of charge by the Bureau de Recherche Géologiques et Minières (BRGM). It is intended for the interpretation of test pumping carried out in hydrogeology, in particular:

Well tests (test by stages of unchained flows)

Groundwater tests (long-term test with constant or variable flow)

It also makes it possible to simulate in a predictive way the evolution of the level of groundwater subject to the effect of a pumping chronicle.

Theis' method allowed us to evaluate the transmissivity of the terminal continental for long-term pumping tests using descent and ascent data.

With u= r2s/4Tt we have Theis' formula which becomes: $s(r,t) = \frac{QW(u)}{4\pi T}$ (2)

The application of Theis' formula is subject to a number of conditions. The following conditions must therefore be met:

- The tested aquifer is captive;
- The aquifer layer is homogeneous, isotropic and of constant thickness in the influenced zone;

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- Complete well: the structure completely penetrates the aquifer and the water flows horizontally over the entire thickness of the aquifer;
- Horizontal piezometric surface before pumping;
- The radius of the borehole is negligible;
- Pumping must be at a constant flow rate and equivalent to the operating flow rate of the structure.

However, not all of these conditions are met, which does not prevent the use of this method for the interpretation of tests (Kouassi, 2012).

- **Determination of drawdown and specific drawdown**

Drawdown represents the lowering of the water level caused by the pumping of groundwater. (Carter et al, 2014). It is represented in meters (m) or feet and represents the difference between the initial piezometric level and the piezometric level during or after pumping. Its mathematical formula is:

$$S = ND - NS \quad (3)$$

S: drawdown ND: dynamic level or piezometric level of water during pumping; NS: static level or water level before pumping

The specific drawdown is the ratio of the drawdown to the corresponding flow. Hydrodynamic values obtained using the long-term and short-term pumping test sheets were compared. We were therefore able to obtain the pumping test data carried out during the installation of certain boreholes in 2001. This comparative study allowed us to see and understand the current functioning of the aquifer after a period of 14 years of intensive pumping to meet the water needs of the population, which continues to grow.

- **Charging Estimate**

  ✓ **Method of fluctuating groundwater levels**

To estimate the recharge of the aquifer over time, we used a first method: that of the fluctuation of the aquifer level. In addition to the fact that piezometric fluctuation analysis (PFA) relies on groundwater data, its attractiveness lies in its simplicity and ease of use and low cost of application. No hypotheses are made about the mechanisms by which water moves through the unsaturated zone. Therefore, the presence of preferential flow paths within the unsaturated zone does not limit its application (Healy and Cook, 2002). The water level measured at one location in an observation is representative of an area of at least several square metres. As a result, AFP can be seen more as an integrated approach than a one-time measure (Healy and Cook, 2002). However, its use is based on a number of constraints (Healy and Cook, 2002; Scanlon *et al*., 2002; Obuobie *et al*., 2012): no disturbance by pumping, no significant delay effect during transit in the unsaturated zone, free aquifer system. When these constraints are met according to Water N. White (1932), recharge can be determined using equation 4 below:

$$R = Sy \times \Delta H \quad (4)$$

With, R: the recharge (in m) between time, Sy: the drainage porosity and ΔH: the variation in the level of the water table (determined with static or piezometric level measurements) (in m).

Over the period from 2011 to 2023, we have had static levels measured regularly by the General Directorate of Water on the various piezometers installed in the municipality of Abomey. Those we used are: the piezometer installed in the locality of Kanssounkpa, in the locality of TOKAN and the one made available to the DGEau by the PAGER project. Indeed, the variation in the level of the water table over a given period corresponds to the variation in static level measured on the same site. This is explained by the formula below which clearly shows that the altitude (m) which is generally characteristic of each region as a function of the relief, is the parameter that differs the static level from the piezometric level.

$$NP = Z - NS \quad (5)$$

With NP: piezometric level (m); Z is the altitude of the place (m); NS is the static level (m).

Over the period from 2023 to 2025, we had data on the piezometric level measured on the F4-1 piezometer of the SONEB and included in the structures of the Godomey Catchment Field.

The Continental Terminal aquifer of the Allada Plateau has a very varied lithology of sand, medium sand, low clay sand and at some levels, sandy clay. To this end, the values of the average effective porosity Sy are chosen on the basis of the work of Boukari M. Alassane A. 2004; Totin V.S.H.; WMO, 2006. The following table presents a synthesis of several studies conducted on the useful porosity, determined by different techniques.

Table 3: Study of the useful porosity of certain soils

Texture	Average effective porosity	Coefficient of variation (%)	Minimum effective porosity	Maximum effective porosity	Number of Determination
Clay	0,02	59	0,00	0,05	15
Ooze	0,08	60	0,03	0,19	16

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Clay sand	0,07	44	0,03	0,12	12
Fine sand	0,21	32	0,10	0,28	17
Medium sand	0,26	18	0,15	0,32	17
Coarse sand	0,27	18	0,20	0,35	17
Gravelly sand	0,25	21	0,20	0,35	15
Fine gravel	0,25	18	0,21	0,35	17
Medium gravel	0,23	14	0,13	0,26	14
Coarse gravel	0,22	20	0,13	0,26	13

Depending on the lithology of the medium and referring to the table, we used a value of the effective porosity Sy equal to 0.26 (medium sand texture) for the calculation of the recharge.

- ✓ **Turk's method for determining effective rain**

In addition to the groundwater level variation method, we used an empirical method, the Turkish method, to determine the effective rainfall that infiltrated and allowed the Continental Terminal to recharge over the period from 2011 to 2025. In 1954, Turc correlated precipitation, temperature and discharge at the outlet of 254 watersheds with varied hydro-climatic characteristics located around the world (Mouelhi, 2011) He derived a relationship between effective rainfall, precipitation and temperature valid at the annual time step (for which the variation in the water stock in the soil is negligible compared to the other terms of the hydrological balance), expressed as follows:

Pe = P – ETR (6)

With Pe: effective precipitation (mm/year); P: total annual precipitation (mm/year); REE: actual evapotranspiration (mm/year) calculated by the Turkic formula.

$$ETR = \frac{P}{\sqrt{0,9+(\frac{P}{L})2}}$$

(7)

With P: annual precipitation in (mm/year); L: temperature-related thermal factor

$$L = 300 + 25T + 0,05T^3$$ (8)

Where T is the annual mean air temperature in °C

By studying the correlations between precipitation and estimated recharge, several authors have proposed empirical relationships to calculate annual recharge directly from precipitation.

To perform the calculation over the period under consideration, we used the ESPERE spreadsheet, which is a software developed by BRGM. Indeed, ESPERE is a Microsoft Excel spreadsheet that allows you to quickly and simultaneously implement a dozen methods for estimating effective rainfall or aquifer recharge. Depending on the data available, the user can choose the methods to be applied among those implemented: three empirical methods (proposed by Guttman, Turc and Kessler), three balance methods (according to Thornthwaite, Dingman and Edijatno & Michel) using daily meteorological data, three methods for filtering flow chronicles (BFI Wallingford, Chapman and Eckhardt) and one method for analysing piezometric variations (Water Table fluctuation).

At the end of the calculations made on the basis of the data we have implemented in the software; we have obtained the effective rainfall over the period from 2011 to 2025.

- ➢ **Study of the volume of water pumped by the Godomey and Ouèdo wellfields over the period from 2011 to 2026**

In order to quantify the demand on the aquifer through the various boreholes in the Godomey and Ouèdo wellfields, we have data on the volume of water pumped over the period from 2011 to 2025. An Excel spreadsheet allowed us to plot the volumes of water pumped as a function of time and to obtain the equation of the regression line in order to closely monitor the amount of water pumped into the aquifer each year and to estimate the effects of this pumping on the aquifer and its discharge during the period under study and to project the potential consequences of this stress over the long term.

Documentation has also enabled us to obtain a chronicle of the operating flows of the various boreholes in operation in order to estimate the daily operating flow rate of the different wellfields and the average daily volume of water pumped today.

- ➢ **Study of the demographic evolution in the Littoral department over the period from 2011 to 2025**

The water pumped from the Godomey and Ouèdo wellfields is intended to serve the population of Cotonou. In order to understand the increase in the volume of water pumped each year, we have listed the areas served and carried out

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a study of the demographic evolution on the basis of the data obtained at the INSTAD. The evolution of the population has explained the high demand for water which continues to increase and consequently the high demand on the aquifer over time. This analysis, which is complementary to our work, has enabled us to project in the long term what the operation of the Continental Terminal would be like and to anticipate the effects of such intensive pumping. An Excel sheet allowed us to study the evolution of the population and to obtain the regression line that we used to project over the years to come.

Results and discussion

- **Hydrodynamic functioning of the Continental Terminal aquifer in 2001**

The diagnosis carried out using data from the F5 Bis borehole drilled in 2001 reveals that the municipality of Abomey-Calavi has an open-water aquifer exploited for the supply of water by the population. The resource is also used by SONEB to serve the population of the commune of Cotonou residing in marshy areas where the consumption of water obtained from the water table is strongly discouraged. Thus, in 2001, this aquifer had a transmissivity of T = 7.97. $^{10-3}$ m2/s and a storage coefficient of S = 10-9 . The assessment of the Nash-Sutcliffe coefficient, which is 0.918, allowed us to confirm the adjustment we had made during the processing of the implemented data. Table 4 provides information on the results of the adjustment of the data from the F5 Bis borehole carried out in June 2001 for the determination of the aquifer parameters.

Table 4: Results of the adjustment of the data of the F5 Bis borehole carried out in June 2001

Adjustment results	Values obtained
Linear Pressure Loss Coefficient (B)	300
Root Pressure Loss Factor (C)	360
Superscript (n)	1,10
Critical throughput	581 m3/hr
Nash-Sutcliffe adjustment coefficient (E)	0,809

The results of this treatment provide information mainly on the productivity of the terminal continental aquifer in 2001. We note a high critical flow rate evaluated at Dc = 581 m ^{3}/h. This critical flow rate makes it possible to understand that in 2001 the Continental Terminal was sufficiently productive and could be used up to a flow rate of this order.

- **Characterization of the hydrodynamic functioning of the Continental Terminal aquifer in 2023**

The processing of this recent pumping test data from 2023 provides information on the hydrodynamic parameters of the Continental terminal in 2023. The Nash coefficient obtained (0.914) reassures us that the parameters are representative over our entire study area. Thus the terminal continental remains a confined aquifer with a transmissivity T = 2.22. $^{10-3m2}$/s and a storage coefficient S = 2.34.10-3.

The results of this adjustment indicate a very low critical flow rate for this completed borehole. Dc = 70.9 m3/h. This flow explains the vulnerability of the aquifer, which can no longer be exploited at high flows when it is captured at its first depths. Table 5 provides information on the results of the adjustment of the F4 borehole data carried out in 2023 for the determination of aquifer parameters.

Table 5: Results of the data adjustment of the F4 drilling drilled in 2023

Adjustment results	Values obtained
Linear Pressure Loss Coefficient (B)	177
Root Pressure Loss Factor (C)	807
Superscript (n)	1,39
Critical throughput	70.9 m3/hr
Nash-Sutcliffe adjustment coefficient (E)	0,997

- **Comparison of the hydrodynamics of the Continental Terminal between 2023 and 2001**

Table 6 presents a comparative study of the hydrodynamic parameters and productivity of the Continental Terminal between 2021 and 2023

Table 6: Comparison of the hydrodynamic parameters of the Continental Terminal between 2001 and 2023

Year	Storage coefficient	Transmissivity	Critical operating flow rate as a function of the depth of the structure
2001	S = 10-9	T = 7.97. 10-3 m2/s	581 m ^{3}/h

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2023 to present	S = 2.34.10-3	T = 2.22. 10-3m2/s	70.9m3/h

- **Current operating flows of the various boreholes in the Godomey and Ouèdo wellfields**

We have had current pumping data from the various boreholes in the Ouèdo and Godomey wellfields to quantify the average hourly and daily load on the aquifer in view of the current critical flow beyond which the continental could be depleted. Graphs 4 and 5 illustrate the current operating flows to which the various boreholes are subjected:

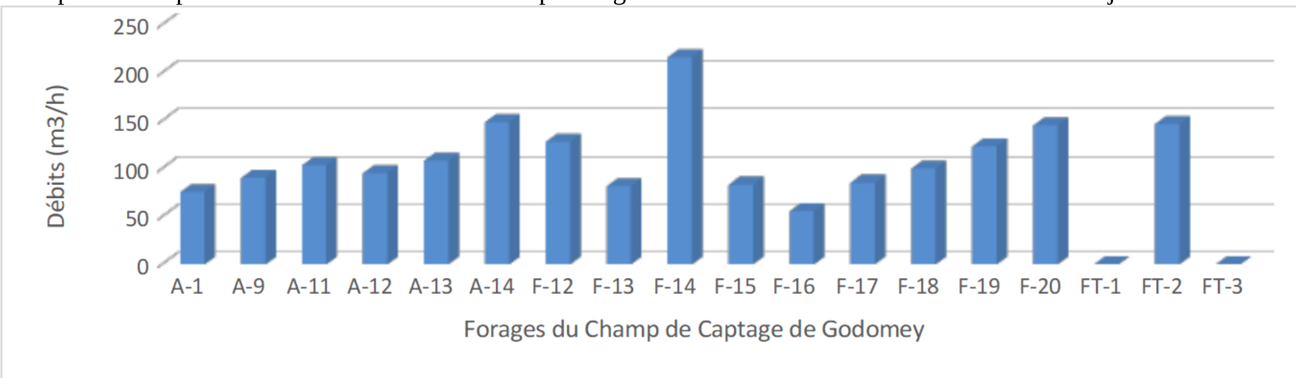

Chart 1: Current pumping flows from the various boreholes in the Godomey wellfields

Source: Documentary research at SONEB

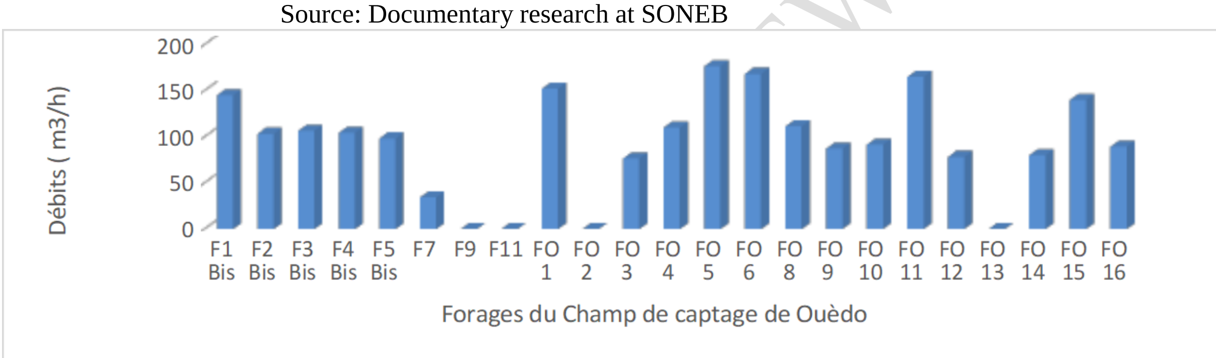

Chart 2: Current pumping flows from the various boreholes in the Ouèdo wellfields

Source: Documentary research at SONEB

The analysis of these different graphs shows that the operating flows of the various boreholes in the Godomey and Ouèdo wellfields are significantly higher than the current critical flow rate of the field. On the Godomey wellfield, borehole F14 produces the highest flow rate at 216 m3/h. As for the Ouèdo field, it hosts the FO5 borehole which extracts the resource at a flow rate of 116 m3/h. However, some boreholes in both fields are out of service, including drill holes FT-1, FT-3, FO 2, FO 13 due to technical failure and drill hole F11 abandoned due to saline intrusion.

- **Estimated recharge of the Continental Terminal over the period from 2011 to 2025**

  - ✓ **Calculation of recharge by the method of variation of the level of the water table**

The groundwater fluctuation method for estimating recharge is based on the determination of the variation in the groundwater over the period considered. Graph 6 shows the annual variations in the water table from 2011 to 2025.

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Chart *3*: Variation in the level of the water table from 2011 to 2025

- Summary of the results and calculation of the annual recharge by the method of variation of the level of the water table

Table 7 shows the recharge and discharge periods observed during each year. Then we proceeded to calculate the variation in the level of the aquifer for the calculation of the recharge of the aquifer expressed in mm over the year. The independent analysis of the fluctuation of the water table during each year since 2011 has led to the following results

Table 7: Results of the recharge balance of the terminal continental from 2011 to 2025 with the method of variation of the water table level

Years	**Charging period**	**Discharge period**	**ΔH (m)**	**Refill (mm)**
2011	1/20/11 – 4/26/11(97 days) And 22/06/11 – 03/12/11(165 days)	4/27/11 – 6/21/11 (56 days)	ΔH1= 0.23 ΔH2= 0.37	156
2012	04/06/12 – 30/07/12 (57 days) and 27/09/12 – 05/12/12 (70 days)	01/01/12 – 03/06/12 (155 days) and 31/07/12 – 26/09/12 (58 days)	ΔH1= 0.12 ΔH2= 0.07	49,4
2013	No charging over the year	01/01/13 – 31/12/13 (365 days)	_	0
2014	8/31/14 – 12/27/14 (119 days)	01/01/14 – 31/08/14 (243 days)	ΔH= 0.12	31,2
2015	5/30/15 – 8/21/15 (84 days)	1/23/15 – 5/30/15 (128 days) and 8/22/15 – 12/31/15 (132 days)	ΔH= 0.1	26
2016	09/07/16 – 07/08/16 (30 days)	_	ΔH= 0.22	57,2
2017	5/13/17 – 11/19/17 (191 days)	_	ΔH= 0.5	130
2018	31/08/18 – 04/10/18 (35 days)	01/01/18 – 31/08/18 (243 days) and 04/10/18 – 06/12/18 (64 days)	ΔH= 0.12	31,2
2019	01/01/19 – 04/06/19 (155 days)And 11/03/19 – 12/31/19 (59 days)	05/06/19 – 02/11/19 (151 days)	ΔH1= 0.07 ΔH2= 0.19	67,6
2020	23/07/20 – 28/07/20 (6 days)		ΔH= 1.32	343,2
2022	01/01/22 – 09/07/22 (190 days) And 20/10/22 – 02/10/22 (44 days)	10/07/22 – 19/10/22 (102 days)	ΔH1=1.14 ΔH2= 1.05	569,4
2023	5/30/23 – 11/08/23 (163 days)	01/01/23 – 23/05/23 (143 days)	ΔH= 1.12	291,2

- ✓ **Calculating Annual Recharge Using the Turk Method**

The Turc mathematical method was used in addition to the groundwater level fluctuation method to calculate the annual effective rainfall. Climatological data such as daily precipitation, potential evapotranspiration (ETP) and average daily temperature allowed us to calculate this effective rainfall over the period of our study. Table 8 presents the results of the various calculations made using the ESPERE tool for the determination of the annual effective rainfall.

Table 8: Results of the annual recharge balance of the continental terminal from 2011 to 2025 using the Turkish method

Annual data			**Intermediate calculations**	**Results**
Year	Precipitationyear-to-date (mm)	Annual mean temperature (°C)	L	Effective Rain (mm)

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2011	1207,1	27,9	2078,3	121,9
2012	1225,1	27,2	1989,7	141,9
2013	943,8	27,5	2030,1	50,5
2014	1329,2	27,6	2038,9	174,5
2015	1135,3	27,3	2000,1	108,4
2016	1168,3	27,8	2070,1	109,9
2017	1139,8	27,4	2016,8	107,6
2018	1176,0	27,7	2061,6	113,6
2019	1484,5	27,4	2017,1	248,1
2020	1275,6	27,6	2044,2	152,2
2021	1037,6	27,9	2076,7	69,9
2022	1240,6	27,5	2023,0	142,4
2023	1552,9	27,4	2019,6	281,2
2024	942,4	27,9	2088,4	45,3
2025	1068,8	27,7	2060,8	80,3

- Assessment of the evolution of water needs and the increase in the population served by the Godomey and Ouèdo wellfields over the period from 2011 to 2025

- ✓ **Assessment of the evolution of the volumes of water pumped from the Godomey wellfields from 2011 to 2025**

Graph 7 shows the evolution of the volume of water pumped from the Godomey wellfield from 2011 to 2025 to monitor the demand on the aquifer over this period. The equation of the regression line makes it possible to estimate the volume of water to be pumped in the coming years following the current pumping rate.

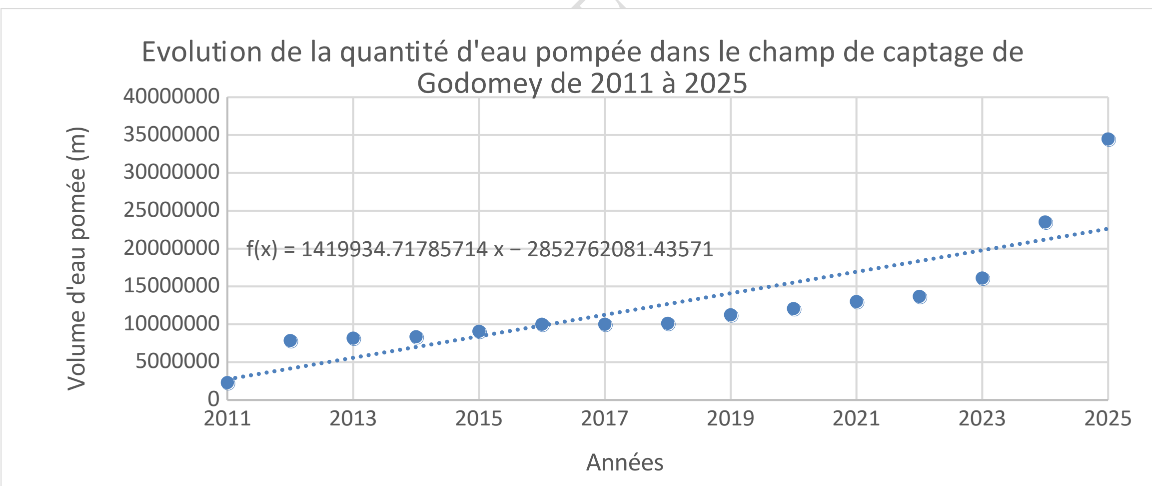

Chart 4: Evolution of the quantity of water pumped from the Godomey wellfield from 2011 to 2025; Source: Documentary research at SONEB

- ✓ **Assessment of the demographic evolution of the population of the Littoral over the period from 2011 to 2025**

The Vèdoko and Godomey treatment plants are responsible for the treatment of water pumped from the Godomey and Ouèdo wellfields to serve the populations of Cotonou. Indeed, the commune of Cotonou is located essentially on a marshy formation. As a result, the water resource captured is not suitable for consumption. The waters of the terminal mainland are therefore used to serve this population, which has been growing rapidly in recent years and according to Instad estimates. To understand the demand on the Continental Terminal, which is increasing every year, we have studied the increase in this population. Chart 8 shows the evolution of the coastal population from 2011 to 2025. The equation of the regression line allows us to make long-term forecasts.

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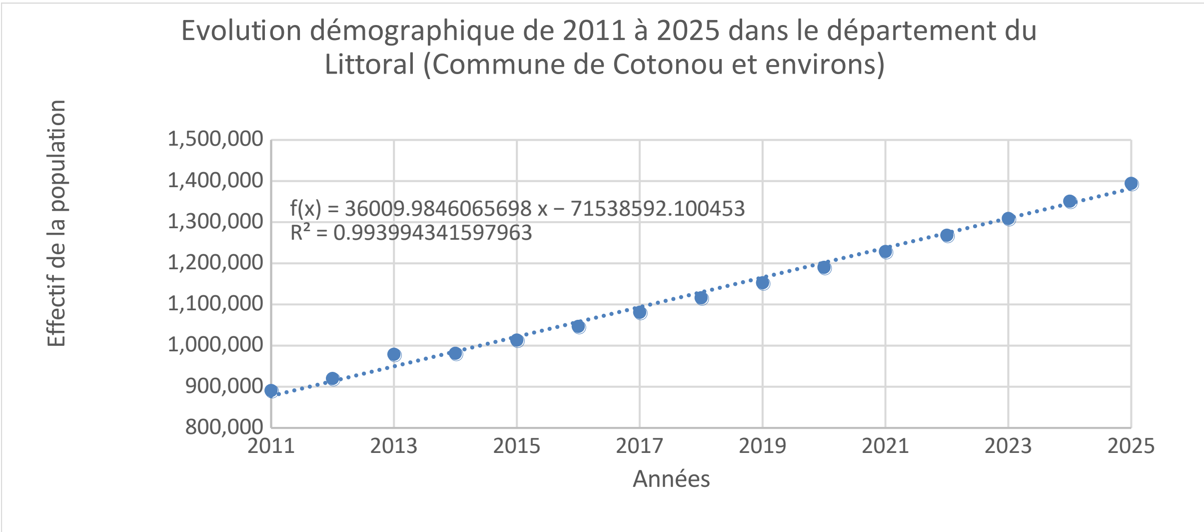

Chart 5: Demographic evolution of the population of Littoral from 2011 to 2025
Source: INSTAD Benin

Discussion

The general objective of this study is to assess the impact of the pumping regime of the Godomey and Ouèdo wellfields on the recharge of the Continental Terminal aquifer. The results obtained reveal considerable changes in the hydrodynamic behaviour of the terminal continental under the effect of anthropogenic pressure and rainfall variability. This discussion is structured around three fundamental axes: the change in hydrodynamic parameters over time, the confrontation between natural recharge and the volumes of water withdrawn, and the analysis of demographic pressure as the main cause of the artificial discharge of the aquifer.

The comparison of the hydrodynamic parameters calculated from the pumping tests shows a decrease in the hydrodynamic properties of the Continental Terminal aquifer between 2001 and 2023. In 2001, the aquifer had a high transmissivity of T= 7.97. 10-3 m2/s and a storage coefficient of 10-9 (reflecting a very marked captive character). Recent data in 2023 indicate a decrease in transmissivity at T= 2.22. 10-3 m2/s and a considerable increase in the storage coefficient to S=2.33. 10-3, testifying to a localized deconfinement of the water table. These observations confirm our first hypothesis and corroborate the work of Boukari et al. , who had anticipated that continuous pumping above the critical flow would cause a restructuring of the flow lines and a decrease in the productivity of the structures in the Godomey sector.

The high critical flow estimated in 2001 shows the initial potential of a virtually virgin or underexploited reservoir. Today, the reduction of this specific productivity to 70.9 m3/h shows that the rate of extraction is approaching the limits of hydrodynamic rupture, thus validating the idea that the aquifer is under hydraulic stress.

The application of the groundwater level fluctuation method (WTF) and the empirical Turc method with the BRGM's ESPERE spreadsheet made it possible to quantify the effective rainfall available for recharge over the period 2011-2025. Using an effective porosity of 0.26 adapted to the middle sand lithology of the Continental Terminal, the analysis highlights a remarkable inadequacy between meteoric inputs and daily exploitation.

Ultimately, the impact of the pumping regime on the recharge balance is not just a simple lowering of piezometric levels; it induces a hydrodynamic mutation of the Continental Terminal. Intensive pumping acts as a powerful artificial discharge sink that disrupts the initial natural hydrodynamic balance (recharge = natural discharge to the outfalls). By modifying the transmissivity and causing the aquifer to deconfinement, the current pumping regime alters the performance of the aquifer in the face of future climatic droughts. If the demographic trends and current extraction rates projected by our regression lines are maintained between now and 2040, the Continental Terminal in South Benin will be exposed to critical stock-outs, a drying up of the shallowest structures and a deterioration in the physico-chemical quality of its waters following a marked saline intrusion that has already begun to affect the aquifer.

Conclusion

This work focused on assessing the impact of the intensive pumping regime on the recharge balance of the Continental Terminal aquifer within the Godomey and Ouèdo wellfields, the main sources of drinking water supply for the municipality of Cotonou. At the end of our investigations, several conclusions emerge with regard to the three specific objectives set. First, the comparative analysis of the hydrodynamic parameters shows a decrease in the

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performance of the aquifer. Between 2001 and 2023, the mean transmissivity dropped by T= 7.97. $^{10-3}$ m2/s at T = 2.22. 10-3 m2/s, while the storage coefficient increased (from S=10-9 to S=2.33. 10-3). These numerical variations reflect a hydrodynamic depletion of the marked aquifer of the sandy reservoir and initiate a local phenomenon of deconfinement of the aquifer, thus validating our first hypothesis. Secondly, the modelling of the water balance using the *ESPERE* tool revealed a chronic imbalance between the diffuse natural recharge (average effective rainfall varying from 50.5 mm to 248.1 mm) and the ever-increasing volumes withdrawn by SONEB. The observed cumulative deficit confirms that the current rates of extraction draw directly from the non-renewable static reserves of the aquifer, confirming the second research hypothesis. Finally, the data on recharge and almost instantaneous discharge cross-referenced with data from the INSTAD show that this artificial discharge is mathematically correlated with the demographic explosion of the municipality of Cotonou.

Faced with the risks of resource depletion, drop in dynamic levels and saline intrusion (marine wedge), we make the following suggestions:

Establishment of an automated piezometric monitoring network: Install real-time remote transmission probes on the Godomey and Ouèdo wellfields to anticipate critical level drops;

Artificial aquifer recharge: Exploring the feasibility of artificial recharge basins upstream of the Allada plateau to collect runoff water and support groundwater piezometry;

Spatial network of wellfields: Increase the number of pumping stations and distribute them evenly throughout the municipality of Abomey-Calavi. This spatial distribution will reduce the individual operating flows of each structure, reducing the amplitude of the local drawdown cones. By limiting stationary hydraulic stress, the resource will be relieved, the assimilation of diffuse recharge will be optimized over the entire basin, and the risk of a rapid advance of saline intrusion will be considerably reduced.

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