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RESEARCH ARTICLE

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

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Abstract

The continental terminal aquifer is the main hydrogeological formation used to supply drinking water to the population of southern Benin. This study examines the impact of the intensive pumping regime of the Ouèdo and Godomey wells on the recharge of the continental terminal aquifer in the municipality of Abomey-Calavi. The methodological approach is based on a comparative analysis of pumping tests between two periods, 2001 and 2023, using the OUAIP software; a model of natural recharge over the period 2011-2025 using the ESPERE tool (groundwater fluctuation methods and the Turc method) with an effective porosity of 0.26 obtained from previous studies in the area; and a statistical forecast estimate based on linear regression line equations intersecting the population growth of the INSTAD (National Institute of Statistics and Aquatic Environments) and the historical volumes of water pumped by SONEB (National Water Company of Benin). The results show a decrease in the hydrodynamic properties of the continental terminal due to intensive pumping. Indeed, the average transmissivity decreased between 2001 and 2023. Concurrently, the storage coefficient increased between 2001 and 2023, reflecting localized deconfinement. The Godomey well field alone experiences an average intensive extraction rate of 47,000 m³ per day, bringing annual withdrawals to 17.2 million m³ for a population already projected to reach 1.3 million inhabitants by 2025. The application of regression line equations shows a linear correlation between population growth and the continental terminal's pumping rate.

Introduction: -

The effectiveness of life on Earth, whether animal, plant, or human, depends on the availability of water resources for each species. Its fundamental and sacred nature explains why it is called the blue water.The most suitable water

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for daily needs, particularly for primary consumption, is groundwater, which represents only 0.76% of the world's available water, serving a population of 8.3 billion. These figures highlight the need for rational resource management to ensure its preservation and sustainability for future generations, as stipulated in the first principle of Integrated Water Resources Management (IWRM): water is essential for life, development, and the environment. Its management must be sustainable to preserve ecosystems. The question arises whether the current pumping regime leads to overexploitation or an imbalance in the water balance. It is in line with previous studies in hydrology and the increasing rate of groundwater exploitation that we focused on the impact of pumping regimes on the recharge balance of the continental terminal aquifer on the Allada plateau: the case of the Godomey and Ouèdo wells in the municipality of Abomey-Calavi (Southern Benin). This study will allow us to assess the impact of groundwater exploitation on natural recharge by comparing the hydrodynamic data of the exploited aquifer over many years with responses to current needs, in order to make future projections and propose concrete solutions for preserving the resource. The overall objective of this study is to evaluate the impact of the pumping regime of the Godomey and Ouèdo wells on the recharge of the continental terminal aquifer of the coastal sedimentary basin in southern Benin.

To achieve this overall objective, we have defined the following specific objectives: -

- Evaluation of the hydrodynamic functioning of the continental terminal aquifer between two different periods; 2001 and 2023
- Estimate the annual recharge of the aquifer over the period from 2011 to 2025
- Assessing the temporal evolution of water needs and population growth depends on the catchment areas of Godomey and Ouèdo over the period from 2011 to 2025.

To guide the research and answer the questions raised by the previously defined objectives, the following research hypotheses are formulated: -

- The continental terminal aquifer of the municipality of Abomey-Calavi would have high transmissivity, but would be subject to a strong constraint, in particular its performance over time;
- The natural recharge of the aquifer would become insufficient to meet annual withdrawals and would be quickly depleted, particularly due to the intensive exploitation of the resource;
- Population pressure and water demand are thought to be the underlying causes of the aquifer extraction rate, which tends to exceed the aquifer's annual recharge capacity.

The context of the study: -

The commune of Abomey-Calavi is located in the Atlantique department of the Republic of Benin. It lies between 6°22' and 6°30' north latitude and 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, representing nearly 20% of the department's area and 0.47% of the national area, with an estimated population of 656,358 in 2013, including 332,784 women and 323,574 men. The commune comprises nine (9) districts: Abomey-Calavi; Akassato; Godomey; Golo-Djigbé; Hévié; Kpanroun; Ouèdo; Togba and Zinvié, as well as one hundred and forty-nine (149) villages and urban districts. (RGPH 4, 2013). Given its proximity to Cotonou, the municipality of Abomey-Calavi is a very dynamic region and popular with the population. Figure 3 illustrates the geographical location of the municipality of Abomey-Calavi.

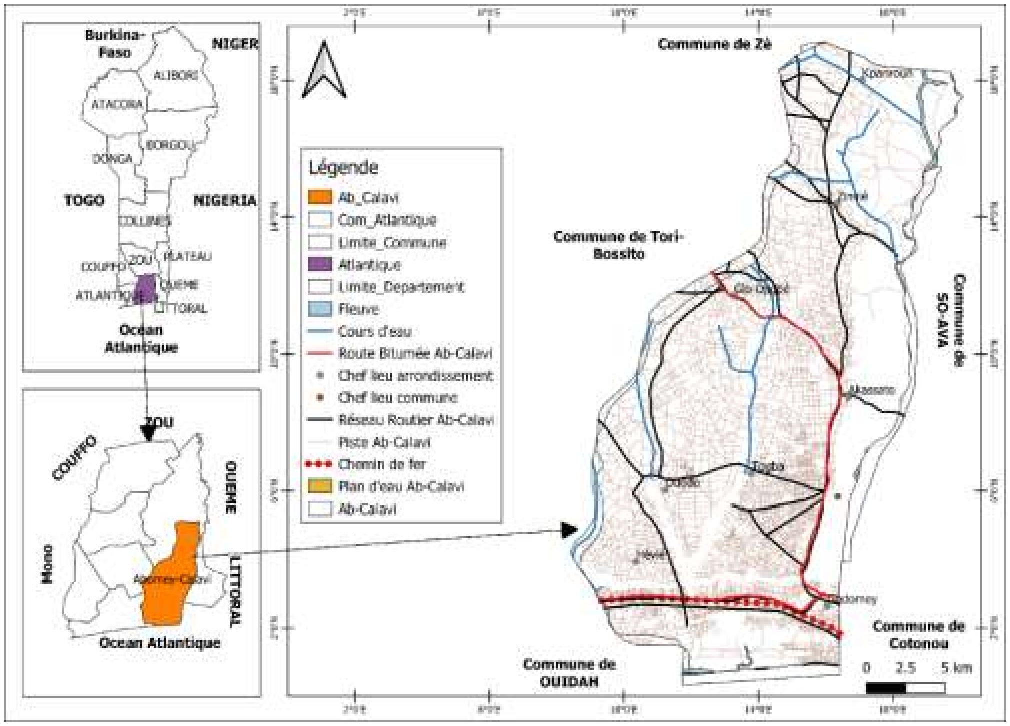


Figure 3 : Geographic map of the municipality of Abomey-Calavi. Source: IGN topographic collection 2018

Geomorphology: -

The geomorphology of the Abomey-Calavi municipality reveals a gently rolling landscape. Its main features are: a plain consisting of a sandy strip with both recent and ancient coastal ridges; a plateau of sandstone separated from the plain by the Djonou River and Lake Nokoué; and depressions and marshes in the areas located on the shores of the lake and lagoon (Departmental Monograph, 2019). The coastal plain has highly permeable soils, which promote rapid infiltration of rainwater and consequently lead to relatively rapid pollution of the groundwater, with a low filtration capacity for the elements carried by the water. The sandstone, on the other hand, has relatively low porosity, making its permeability less pronounced than that of the coastal plain formations. Figure 5 below presents the geomorphological map of the Abomey-Calavi municipality.

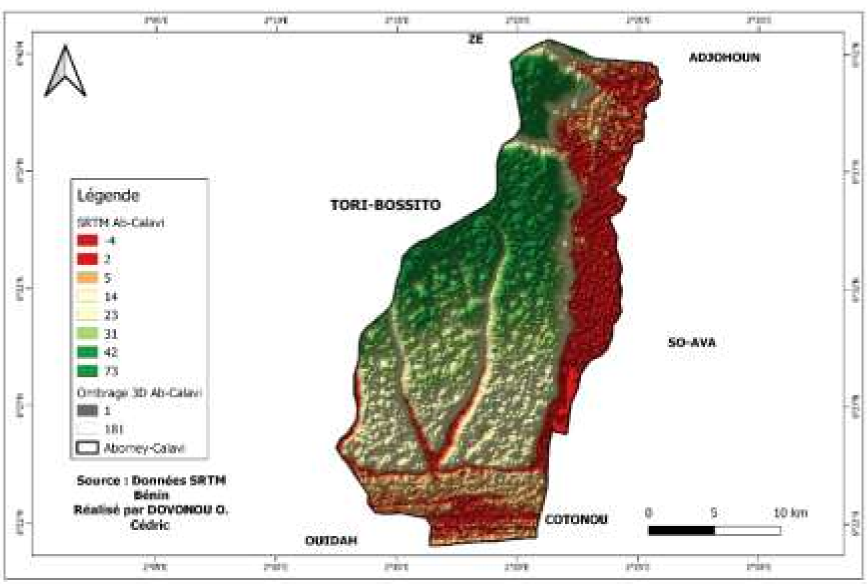


Figure 1: Geomorphological map of the municipality of Abomey-Calavi; Source: SRTMBénin data

Hydrography:-

The hydrographic network consists primarily of two bodies of water: Lake Nokoué and the Djonou River. In addition, the municipality has a coastline adjacent to the coastal lagoon (Togbin Lagoon), as well as marshes, streams, and swamps. Figure 6 illustrates the hydrographic network of the municipality of Abomey-Calavi and its surrounding area.

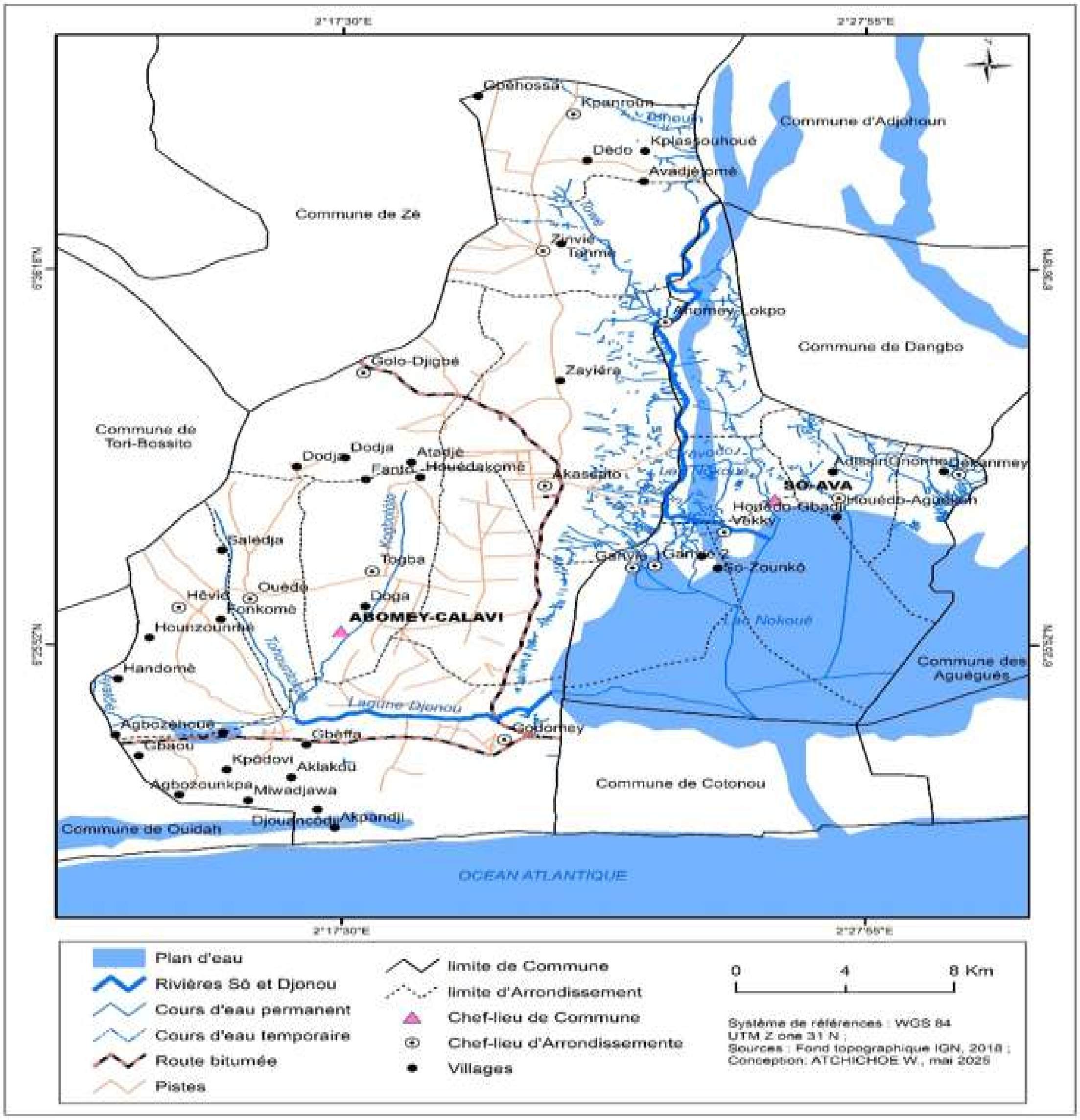


Figure 2: Hydrographic map of the Commune of Abomey-Calavi and its surroundings. Source: Doctoral thesis, ATCHICHOE W., May 2025

Materials: -

To carry out this work, we used state-of-the-art computer tools with data processing software, in accordance with our needs and the objectives set before we began the project. We used an HP Elitebook × 360 830 G6 laptop with 250 gigabytes of storage for the data we collected; Excel 2019 for statistical data processing; Word 2019 for word processing; QGIS Desktop 3.10.8 with GRASS 7.8.3 for map creation; ESPERE software for recharge estimation using several implemented methods; and OUAIP_v3.1-R13 software for processing and interpreting pumping test data, as well as digital terrain models and shapefiles, and raster data for complete map production and elevation extraction. In addition to all this computer equipment, we collected data from various structures, the processing and interpretation of which allowed us to achieve the objectives we set for ourselves.

Methods: -

Literature search: -

The first step was to conduct a well-structured literature search, which allowed us to contextualize our work, review existing research, and clearly define our objectives and guide our research. We consulted and utilized older dissertations, as well as articles, publications, and theses on topics related to our own. We visited the Benin Library of Excellence at the Valley Foundation and the library of the National Water Institute to access physical documents and consulted online resources on various scientific websites. All of this documentation provided us with data on the geographic location, hydrography, pedology, geology, hydrogeology, and geomorphology of our study area, as well as historical SONEB (National Water Company of Benin) production and demographic data.

Data collection: -

This step follows the documentary research we described above. We therefore went to the relevant organizations to collect data and technical information on our study area. To this end, we visited the Departmental Directorate of Energy, Water and Mines of the Atlantic Coast (DDEEM Atl-Lit), as well as the General Directorate of Water, the National Water Company of Benin (SONEB), and the International Institute of Tropical Agriculture (IITA) to gather the following information:Data from long- and short-term pumping tests carried out in the municipality of Abomey-Calavi (data obtained from DDEEM Atl-Lit);Data from pumping tests (short and long term) carried out in 2001 during the drilling of certain forages in the well;Monitoring data from the piezometers of the Ouèdo and Godomey wells (data obtained from SONEB and the General Directorate of Water);Data for the climatic period 2011 to 2025 (data obtained from IITA);Operational data for the forages of the Godomey and Ouèdo wells (operating flow rates, geographical coordinates of the different forages);Data on the annual volume of water pumped from the well fields of Godomey over the period from 2011 to 2025 (data obtained from SONEB).The data used to determine the hydrodynamics of the Continental terminal between two different periods consists of pumping test data from tests conducted in the Abomey-Calavi area. These tests involved pumping operations, and the information (static level, dynamic level, drawdown) was recorded over a long period.

Data processing: -

The processing of the obtained data was carried out in accordance with our objectives. We began by estimating productivity, then proceeded to determine specific discharge, aquifer transmissivity, simple deployment, and specific discharge for Specific Objective 1, which is to characterize the hydrodynamic functioning of the aquifer using data from long and short pumping tests conducted in the municipality of Abomey-Calavi. As for Specific Objective 2, which is to evaluate the aquifer recharge balance using the Turc method and the piezometric fluctuation method, we described and processed each of the necessary data, in particular the climatological data and the piezometric monitoring data of water levels collected from the well fields of Godomey and Ouèdo. Finally, to address specific objective 3 concerning the study of the annual volume of water pumped, the population growth of the communities served by the Godomey and Ouèdo fields, and the overall population, we produced a table showing the annual variation in water needs, represented by the volume of water pumped over time and by population growth, in order to correlate this population, increase with resource exploitation. The following paragraphs describe the methodology adopted for each step.

Productivity estimation: -

The productivity of an aquifer is its capacity to provide a minimum exploitable flow rate through the channel of a watershed structure (Gombert, 1997). For a better assessment of well flow rates, the Inter-African Committee for Hydraulic Studies (CIEH) proposed the following classification (Lams et al., 2000).

Table 1: Evaluation of operational flow rates of a hydrogeological structure (Lams et al., 2000)

Debits	Assessment
0 – 1 m3/h	Very low
1 – 2.5 m3/h	Weak
2.5 – 5 m^3/h	Average
>5 m3/h	Strong

As for transmissivity, it was calculated using Theis' method with available structural degradation data during and after pumping was stopped during the rise. The following classification allows for transmissivity analysis (Lams et al., 2000).

Table 2: Evaluation of the transmissivity of an aquifer

Transmissivity	Assessment
T <$^{10^{-5}}$ m²/s	Weak
$^{10^{-5}}$ m²/s < T < 10^{-4} m²/s	Average
T >$^{10^{-4}}$ m²/s	Strong

Determination of specific flow rate: -
The characteristics of a structure and its immediate surroundings are determined by pumping tests performed in the environment. These pumping tests allow us to evaluate the critical flow rate, the relative specific flow rate, the critical flow rate of the structure, and the various pressure troughs subjected to pumping. To determine these different parameters, we have several pumping data sets available for each stage. The specific flow parameter (ratio between flow rate and discharge) is calculated from the flow rate values of the first stage and the discharge rate s (m). We limited ourselves to the first stage to reduce the influence of squared pressure losses on the pumping structures. The mathematical expression for 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)

Determination of transmissibility: -
Transmissivity is a fundamental hydrodynamic property that measures an aquifer's capacity to transmit water throughout its saturated thickness. It expresses the flow rate of water per unit width of the aquifer under the influence of a unit hydraulic gradient (Castany et al., 1982). We work with data from a forage sample taken during a long-term pumping test. To successfully process these data, we used the pumping test interpretation tool (OUAIP software), which allowed us to interpret long- and short-term pumping test data using the Theis method. The OUAIP software is a tool developed and distributed free of charge by the French Geological Survey (BRGM).

It is designed for the interpretation of pumping tests carried out in hydrogeology, specifically: -
Well tests (unchained flow step tests) Groundwater testing (long-term tests with constant or variable flow) This also allows for predictive simulation of the evolution of groundwater levels subjected to the effect of a pumping history.
Theis' method allowed us to evaluate the transmissivity of the continental terminal for long-term pumping tests using descent and ascent data.

with you = r2s/4Tt on a Theis formula which becomes: -
$s(r,t) = \frac{QW(u)}{4\pi T}(2)$

The application of Theis' formula is subject to several conditions. The following conditions must therefore be met: -
- The tested aquifer is confined;
- The aquifer layer is homogeneous, isotropic and of constant thickness in the affected area;
- Full well: the structure completely penetrates the aquifer and the water flows horizontally through the entire thickness of the aquifer;
- Horizontal piezometric surface before pumping;
- The radius of the fodder is negligible;
- Pumping must be done at a constant flow rate 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). The application of Theis's (1935) analytical solution in hydrogeology relies on a series of rigorous simplifying assumptions, rarely verified in complex, real-world aquifer systems. The method assumes a confined, homogeneous, and isotropic aquifer of infinite spatial extent and constant thickness, bounded by impermeable upper and lower layers. In this model, groundwater flow to the pumping well is strictly radial and horizontal, with instantaneous release of the stored water upon a drop in the water level. In natural environments, such as the heterogeneous sedimentary formations of the Continental Terminal, these idealized conditions encounter several major limitations: the spatial variability of lithological facies (heterogeneity of hydraulic conductivity and transmissivity), the time lag in water inflow due to permeable or semi-confined layers (aquitard leaks), local or regional transitions between confined and free/semi-confined states during significant water level drops, seasonal variations in vertical recharge, and the effects of natural hydrogeological boundaries (recharge limits, surface water

bodies, saline interfaces, or impermeable faults). Furthermore, extrapolating storage coefficients or transmissivity values derived from localized pumping tests interpreted using the Theis equation can mask regional aquifer depletion or introduce significant errors in long-term drawdown forecasts and regional water balance assessments.
To overcome these constraints, three-dimensional numerical modeling of groundwater flow (using finite difference or finite element codes, such as MODFLOW) is a much more suitable approach. Unlike point-based analytical methods, a numerical model integrates the geometric architecture and spatial variability of the reservoir's hydrodynamic properties (transmissivity and effective porosity distributions derived from geostatistical interpolation), realistic geological and hydrological boundary conditions (specified flow and hydraulic head, surface infiltration interfaces), historical pumping rates, and spatially variable recharge from climatic water balances (e.g., via ESPERE), and simulates the dynamic transition between confined, semi-confined, and unconfined regimes.

In practice, establishing such a model involves four fundamental steps:Development of the conceptual model, defining the multilayer geometry, the discretization of the spatial grid and the boundary conditions of the study domain;Calibration of the model in steady state and transient regime, by adjusting the hydraulic parameters (hydraulic conductivity, specific storage, specific efficiency) by matching the calculated hydraulic heads to the time series of long-term piezometric observations;Sensitivity analysis and validation, in order to quantify predictive uncertainty in relation to the variability of the input data; and Predictive scenario simulations provide a decision support tool to assess the long-term impacts of various pumping regimes (population projections and increased water demand), evaluate artificial recharge strategies and anticipate the risks of aquifer overexploitation and saltwater intrusion.

Determination of the reduction and the specific reduction: -

Drawdown represents the drop in water level caused by groundwater pumping (Carter et al., 2014). It is expressed 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 as follows: -

$$S = ND - NS \tag{3}$$

S: Suction; ND: Dynamic or piezometric water level during pumping; NS: Static or water level before pumping
Specific discharge is the ratio between the discharge and the corresponding flow rate. Hydrodynamic values obtained using long- and short-term pumping test sheets were compared. We were thus able to obtain data from pumping tests carried out during the installation of certain forage crops in 2001. This comparative study allowed us to observe and understand the current functioning of the aquifer after a period of 14 years of intensive pumping to meet the ever-increasing water needs of the population.

Estimate of the recharge: -

Method for fluctuating groundwater levels: -

To estimate aquifer recharge over time, we used a first method: aquifer level fluctuation analysis. In addition to the fact that piezometric fluctuation analysis (PFA) relies on groundwater data, its appeal lies in its simplicity, ease of use, and low application cost. No assumptions are made about the mechanisms by which water flows through the unsaturated zone. Consequently, the presence of preferential flow paths in the unsaturated zone does not limit its application (Healy and Cook, 2002). The water level measured at a given location during an observation represents an area of at least several square meters. As a result, PFA can be viewed more as an integrated approach than as a single measurement (Healy and Cook, 2002). However, its use is subject to several constraints (Healy and Cook, 2002; Scanlon et al., 2002; Obuobieet al., 2012): no pumping disturbance, no significant delay effect during transit through the unsaturated zone, and a free aquifer system. When these constraints are met according to Water N.

White (1932), recharge can be determined using Equation 4 below: -

$$R = Sy \times \Delta H \tag{4}$$

With R: the recharge (in m) between times, Sy: the porosity of the drainage and ΔH: the variation of the groundwater level (determined by static or piezometric measurements of the level) (in m).

Between 2011 and 2023, static water levels were regularly measured by the General Directorate of Water (DGEau) at various piezometers installed in the municipality of Abomey. The piezometers we used were those installed in the locality of Kanssounkpa, in the locality of Tokan, and the one provided to the DGEau by the PAGER project. Indeed, the variation in the groundwater level over a given period corresponds to the variation in the static water level measured at the same site. This is explained by the formula below, which clearly shows that altitude (in meters), generally characteristic of each region according to its topography, is the parameter that differentiates the static water level from the piezometric water level.

PN = Z – NS (5)

With NP: piezometric level (m); Z is the altitude of the location (m); NS is the static level (m). Over the period from 2023 to 2025, we had data on the piezometric level measured on the SONEB F4-1 piezometer and included in the structures of the Godomey catchment. The continental terminal aquifer of the Allada plateau exhibits a highly varied lithology composed of sand, medium sand, weak clayey sand, and, at certain levels, sandy clay. For this purpose, the average effective porosity (Sy) values were chosen based on the work of Boukari M. Alassane A. (2004) and Totin VSH (2006). The following table presents a synthesis of several studies conducted on effective 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 determinations
Clay	0.02	59	0.00	0.05	15
Mud	0.08	60	0.03	0.19	16
Clayey sand	0.07	44	0.03	0.12	12
Sand fin	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

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

The Turkish method for determining effective rainfall: -

In addition to the groundwater level variation method, we used an empirical method, the Turc method, to determine the effective precipitation that infiltrated and allowed the continental terminal to recharge over the period from 2011 to 2025. In 1954, Turc correlated the withdrawals, temperature, and discharge at the outlet of 254 watersheds with varying hydroclimatic characteristics worldwide (Mouelhi, 2011). He established a relationship between effective withdrawals, discharges, and temperature valid on an annual scale (for which the variation in soil water stock is negligible compared to the other terms of the water balance), expressed as follows:

Pe = P – ETR (6)

With Pe: effective withdrawal (mm/year); P: total annual withdrawals (mm/year); REE: actual evapotranspiration (mm/year) calculated according to the Turkish formula.

$$\mathrm{ETR} = \frac{P}{\sqrt{0,9+(\frac{P}{L})2}} (7)$$

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

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

Where T is the average annual air temperature in °C

By studying the correlations between withdrawals and estimated recharge, several authors have proposed empirical relationships to calculate annual recharge directly from withdrawals. To perform the calculation over the period studied, we used the ESPERE spreadsheet, software developed by BRGM. ESPERE is a Microsoft Excel spreadsheet that allows you to quickly and simultaneously implement a dozen methods to estimate the effective recharge of water withdrawals or the aquifer. Depending on the available data, the user can choose which methods to apply from those implemented: three empirical methods (proposed by Guttman, Turc, and Kessler), three equilibrium methods (according to Thornthwaite, Dingman, and Edijatno& Michel) using daily meteorological data, three methods for filtering flow records (BFI Wallingford, Chapman, and Eckhardt), and a method for analyzing piezometric variations (fluctuations in the water table). The empirical method of Turc (1954, 1961) is a widely used hydro-climatic approach for estimating annual Actual Evapotranspiration (AET) at the scale of a watershed or region. This parameter is fundamental for determining, by subtraction from total precipitation, the depth of water available for runoff and aquifer recharge. Based on the analysis of hydrological balances observed in numerous watersheds worldwide, the method relies on the main assumption of an average annual water equilibrium regime (the variation in soil water stock is assumed to be negligible over a complete annual cycle $\Delta S \approx 0$), where AET depends primarily on water availability (precipitation) and the evaporative power of the atmosphere (air temperature).

The input parameters required for its implementation are thus limited to rainfall (Por P_m) and temperature (Tor T_m), supplemented by monthly radiation or insolation data (I_g). The main limitations of this residential-scale method lie in its empirical and global nature: it does not take into account the available soil water capacity (ASW), vegetation dynamics (leaf area index, specific transpiration), or extreme rainfall events daily, which can lead to biases in the estimation of evapotranspiration (ETR) and effective recharge in climates with strong seasonal rainfall or in highly draining soil contexts. At the end of the calculations carried out on the basis of the data that we implemented in the software; we obtained the actual withdrawals for the period from 2011 to 2025.

Study of the volume of water pumped from the Godomey and Ouèdo wells over the period from 2011 to 2025: -

In order to quantify the demand on the aquifer through the different forages in the fields of Godomey and Ouèdo, 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 from the aquifer each year, to observe the effects of this pumping on the aquifer and its flow during the period studied and to project the potential consequences of this stress in the long term. The documentation also allowed us to obtain a record of the operational flow rates of the different active forages in order to assess the daily flow rate of the different wells and the average daily volume of water pumped today.

Study of the demographic evolution of the Littoral department over the period from 2011 to 2025: -

The water pumped from the Godomey and Ouèdo wells is intended to supply the population of Cotonou. To understand the increase in the volume of water pumped each year, we identified the areas served and conducted a demographic study based on data obtained from INSTAD. Population growth explains the high and ever-increasing demand for water, and consequently, the high demand on the aquifer over time. This analysis, complementary to our work, allowed us to project the long-term operation of the continental terminal and anticipate the effects of such intensified pumping. An Excel spreadsheet enabled us to study population trends and obtain the regression line we used for future projections.

Results and Discussion: -

Hydrodynamic functioning of the continental terminal aquifer in 2001: -

The analysis of data from the F5 Bis borehole drilled in 2001 revealed that the municipality of Abomey-Calavi possesses an open-water aquifer used to supply water to the population. This resource is also used by SONEB (the national water utility) to serve the population of Cotonou living in marshy areas where the consumption of groundwater is strongly discouraged. In 2001, this aquifer had a transmissivity of T = 7.97 $^{x\ 10^{-3}}$ m²/s and a storage coefficient of S = 10^{-9}. The Nash-Sutcliffe coefficient, which is 0.918, confirmed the adjustment made during the data processing. Table 4 provides information on the results of the adjustment of the F5 Bis borehole data carried out in June 2001 to determine the aquifer parameters.

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

Adjustment results	Values obtained
Linear pressure loss coefficient (b)	300
Radicular pressure loss factor (C)	360
Presentation (n)	1.10
Flow rate review	581 m³/h
Nash-Sutcliffe adjustment coefficient (E)	0.809

The results of this analysis are primarily based on information regarding the productivity of the continental terminal aquifer in 2001. We note a high critical flow rate estimated at Dc = 581 m^3/h. This critical flow rate indicates that in 2001, the continental terminal aquifer was sufficiently productive and could be used up to a flow rate of this magnitude.

Characterization of the hydrodynamic functioning of the continental terminal aquifer in 2023: -

The processing of these recent pumping test data from 2023 provides information on the hydrodynamic parameters of the Continental terminal in 2023. The obtained Nash coefficient (0.914) confirms that the parameters are representative of our entire study area. Thus, the Continental terminal remains a confined aquifer with a transmissivity $T = 2.22 \times 10^{-3}\ m^2/s$ and a storage coefficient $S = 2.34 \times 10^{-3}$. The results of this adjustment indicate a very low critical flow rate for this finished forage, Dc = 70.9 m^3/h. This explains the vulnerability of the aquifer, which can no longer be exploited at high flow rates when it is captured at its shallowest depths. Table 5 provides information on the results of the adjustment of the F4 forage data carried out in 2023 for the determination of aquifer parameters.

Table 5: Results of the adjustment of F4 forage data carried out in 2023

Adjustment results	Values obtained
Linear pressure loss coefficient (b)	177
Radicular pressure loss factor (C)	807
Presentation (n)	1.39
Debit rating	70.9 m^3/h
Nash-Sutcliffe adjustment coefficient (E)	0.997

Comparison of the hydrodynamics of the continental terminal between 2023 and 2001:-

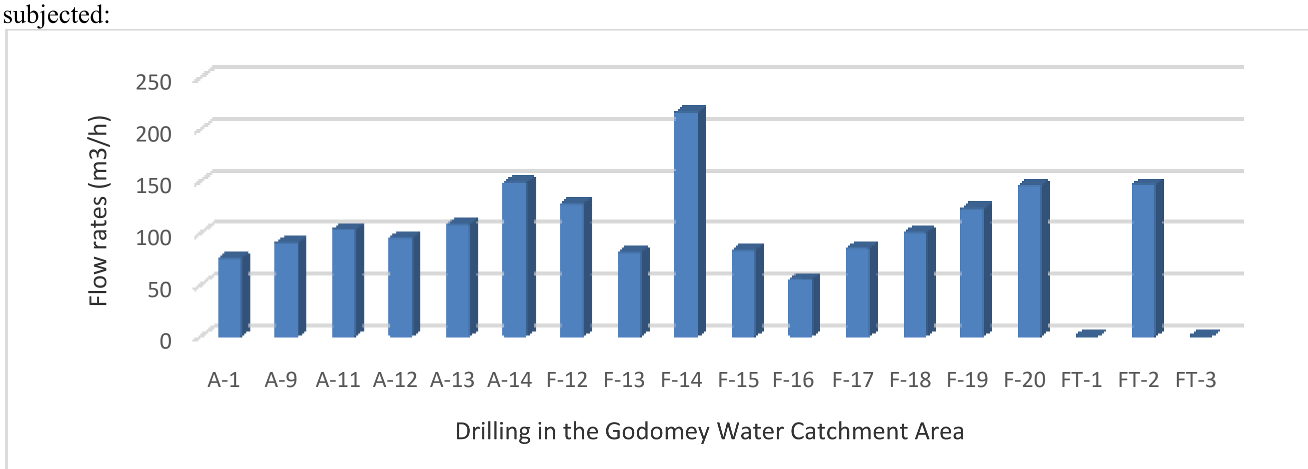
Table 6 presents a comparative study of the hydrodynamic parameters and productivity of the Continental Terminal between 2001 and 2023

Table 6: Comparison of hydrodynamic parameters of the continental terminal between 2001 and 2023

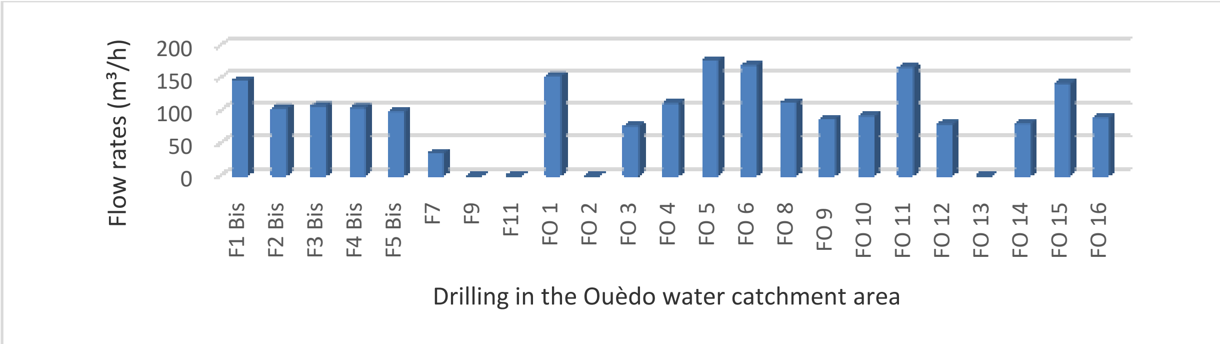
Year	Storage coefficient	Transmissivity	Critical operating flow rate as a function of structure depth
2001	$S = 10^{-9}$	$T = 7.97 \times 10^{-3}\ m^2/s$	581 m^3/h
From 2023 to today	$S = 2.34 \times 10^{-3}$	$T = 2.22 \times 10^{-3}\ m^2/s$	m^3/h**70.9**

Current flow rates of the various forages from the Godomey and Ouèdowells:-

We received current pumping data from the various wellheads in Ouèdo and Godomey to quantify the average hourly and daily load on the aquifer, taking into account the current critical flow rate beyond which the mainland aquifer could be depleted. Figures 4 and 5 illustrate the current operating flows to which the different wellheads are subjected:



Classification 1: The pumping current flows from the various wells of Godomey
Source: Document research at SONEB



Classification 2: The pumping current flows from the various wells of the Ouèdo wells
Source: Document research at SONEB

Analysis of these graphs shows that the extraction rates of the various wells in the Godomey and Ouèdo fields are significantly higher than the field's current critical flow rate. At the Godomey well, well F14 produces the highest flow rate at 216 m³/h. As for the Ouèdo field, it houses well FO5, which extracts the resource at a rate of 116 m³/h. However, some wells in both fields are out of service, notably wells FT-1, FT-3, FO2, and FO13 due to a technical failure, and well F11, abandoned due to saline intrusion, as documented in our records at the SONEB archives.

Estimated reloading of the continental terminal for the period from 2011 to 2025: -
Calculation of recharge using the groundwater level variation method: -

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

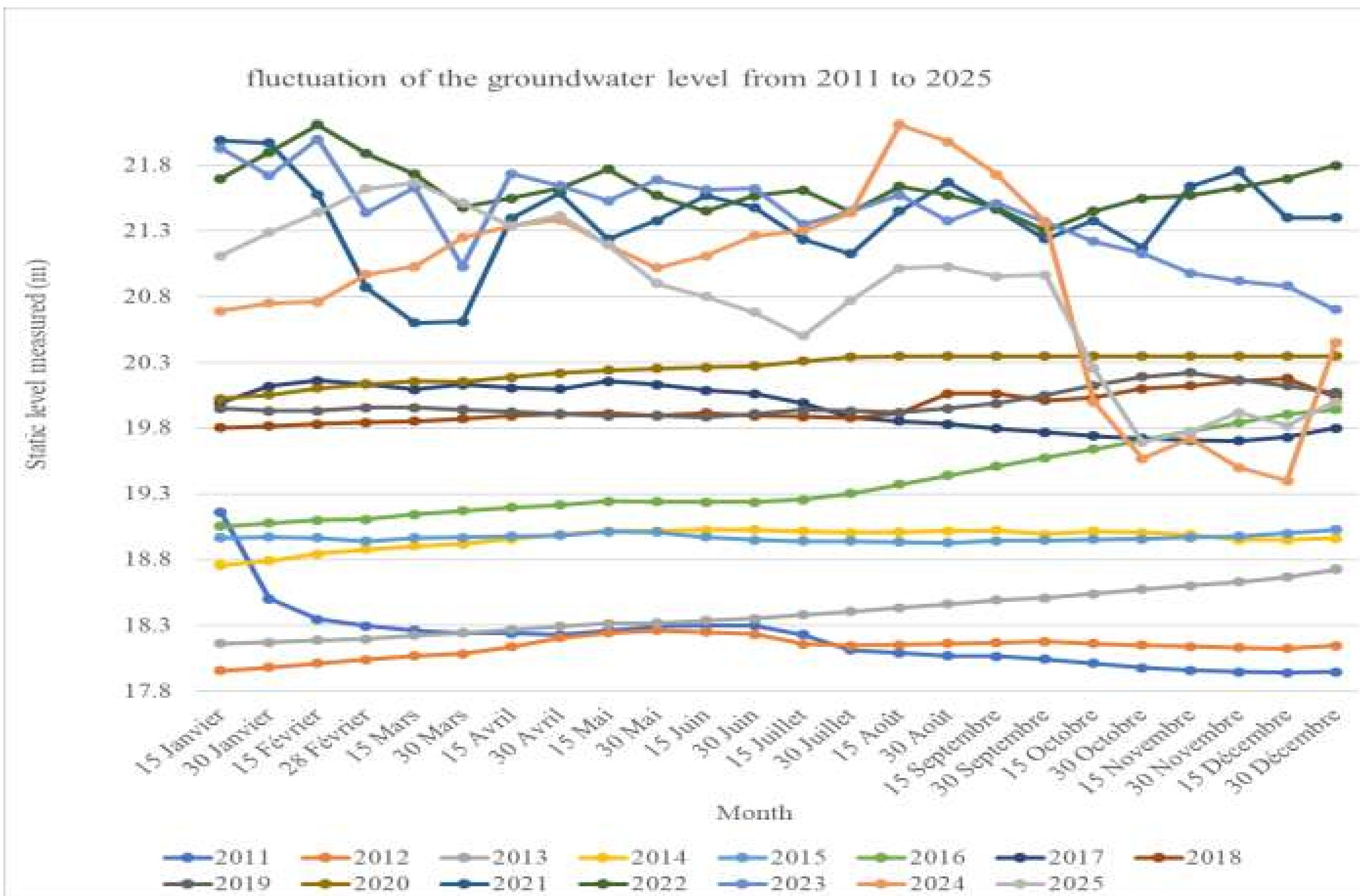


Figure 3: Variation in groundwater level from 2011 to 2025

Summary of results and calculation of annual recharge using the groundwater level variation method:-
Table 7 presents the recharge and discharge periods recorded each year. We then calculated the variation in the aquifer level to determine the annual aquifer recharge, expressed in mm. Independent analysis of groundwater fluctuations each year since 2011 yielded the following results:

Table 7: Results of the recharge balance of the continental terminal from 2011 to 2025 using the groundwater level variation method

Years	Charging period	Release period	ΔH (m)	Refill (mm)
2011	20/01/11 – 26/04/11 (97 days) And from 22/06/11 to 03/12/11 (165 days)	27/04/11 – 21/06/11 (56 days)	ΔH1 = 0.23 ΔH2 = 0.37	156
2012	04/06/12 – 30/07/12 (57 days) and 27/09/12 – 12/05/12 (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 annual billing	01/01/13 – 31/12/13 (365 days)	_	0
2014	31/08/14 – 27/12/14 (119 days)	01/01/14 – 31/08/14 (243 days)	ΔH = 0.12	31.2
2015	30/05/15 – 21/08/15 (84 days)	23/01/15 – 30/05/15 (128 days) and 22/08/15 – 31/12/15 (132 days)	ΔH = 0.1	26
2016	07/09/16 – 08/07/16 (30 days)	_	ΔH = 0.22	57.2
2017	13/05/17 – 19/11/17 (191 days)	_	ΔH = 0.5	130
2018	31/08/18 – 04/10/18 (35 days)	01/01/18 – 31/08/18 (243 days) and 10/04/18 – 12/06/18 (64 days)	ΔH = 0.12	31.2
2019	01/01/19 – 04/06/19 (155 days) And 03/11/19 – 31/12/19 (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 – 02/10/02/22 (44 days)	07/10/22 – 19/10/22 (102 days)	ΔH1=1.14 ΔH2 = 1.05	569.4
2023	30/05/23 – 08/11/23 (163 days)	01/01/23 – 23/05/23 (143 days)	ΔH = 1.12	291.2

Calculation of the annual recharge according to the Tur c method: -
Turc's mathematical method was used in addition to the groundwater level fluctuation method to calculate effective annual water withdrawals. Climatological data such as daily withdrawals, potential evapotranspiration (PET), and daily mean temperature allowed us to calculate these effective withdrawals over the study period. Table 8 presents the results of the various calculations performed using the ESPERE tool to determine effective annual rainfall.

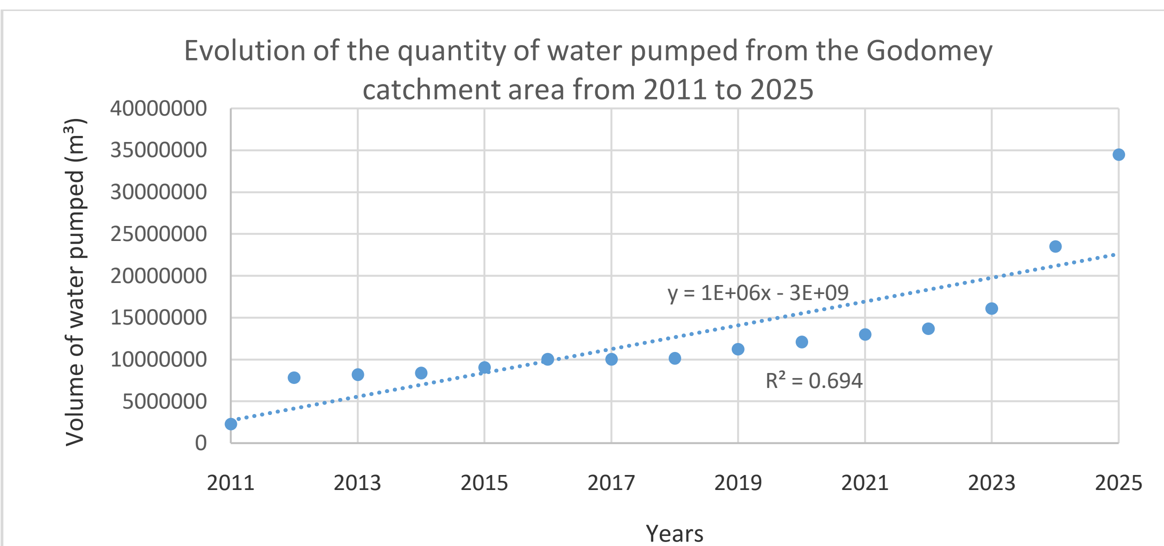
Table 8: Results of the annual recharging balance of the continental terminal from 2011 to 2025 using the Turkish method

	Annual data		Intermediate calculations	Results
Year	Rainfall since the beginning of the year (mm)	Average annual temperature (°C)	L	Effective rainfall (mm)
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 wells of Godomey and Ouèdo over the period from 2011 to 2025:-

Evaluation of the evolution of water volumes pumped from the well fields of Godomey from 2011 to 2025:-

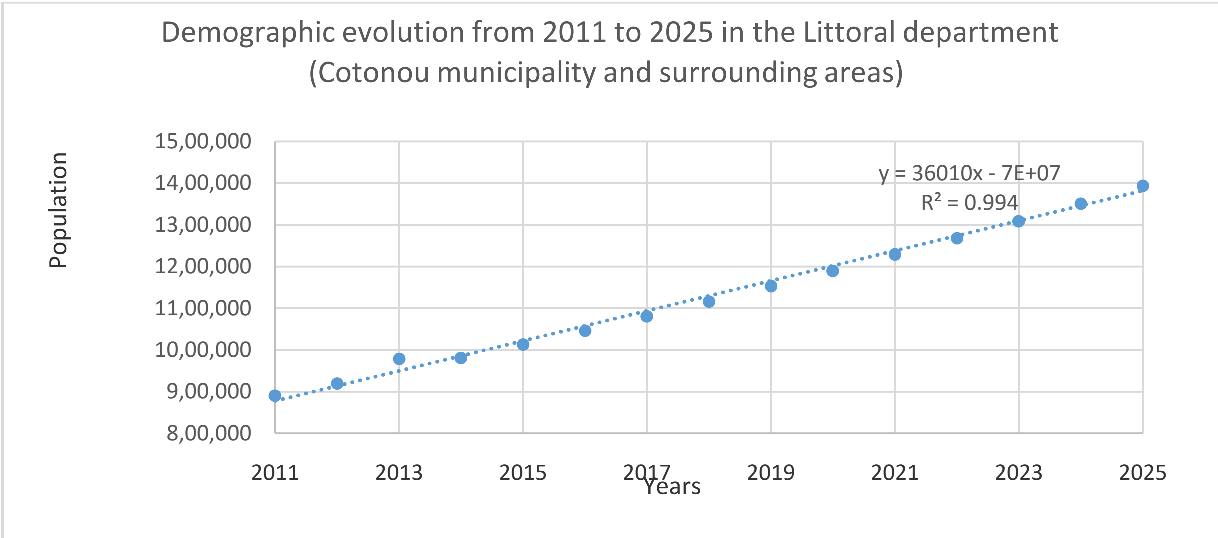
Figure 7 shows the evolution of the volume of water pumped from the Godomey well from 2011 to 2025 to monitor the demand on the aquifer over this period. The regression line equation allows us to estimate the volume of water to be pumped in the coming years based on the current pumping rate.



Ranking 4: Evolution of the quantity of water pumped from the Godomey well field from 2011 to 2025; Source: Document research at SONEB

Assessment of the demographic evolution of the coastal population over the period from 2011 to 2025:-

The Vèdoko and Godomey wastewater treatment plants are responsible for treating water pumped from the Godomey and Ouèdo wells to supply the population of Cotonou. Indeed, the municipality of Cotonou is primarily situated on marshland. Consequently, the captured water resource is not suitable for consumption. Water from the Continental Terminal is therefore used to serve this population, which has experienced rapid growth in recent years, according to Instat estimates. To understand the demand at the Continental Terminal, which increases every year, we studied the growth of this population. Graph 8 shows the evolution of the coastal population from 2011 to 2025. The equation of the regression line allows us to make long-term projections.



Ranking 5: Demographic evolution of the coastal population from 2011 to 2025
Source: INSTAD Benin

Discussion: -

The overall objective of this study is to evaluate the impact of the pumping regime of the Godomey and Ouèdo well fields on the recharge of the Continental Terminal aquifer. The results obtained reveal considerable changes in the hydrodynamic behavior of the Continental Terminal under the influence of anthropogenic pressure and rainfall variability. This discussion is structured around three fundamental axes: changes in hydrodynamic parameters over time, the comparison between natural recharge and extracted water volumes, and the analysis of population pressure as the main cause of the aquifer's artificial discharge.

Comparison of hydrodynamic parameters derived from pumping tests shows a decline in the hydrodynamic properties of the Continental Terminal aquifer between 2001 and 2023. In 2001, the aquifer exhibited a high transmissivity of 7.97×10^{-3} m² / s and a storage coefficient of 10^{-9}, indicating a very pronounced confined character. Data collected in 2023 indicate a decrease in transmissivity to 2.22×10^{-3} m² / s and a considerable increase in the storage coefficient to 2.33×10^{-3}, demonstrating localized release of the aquifer. These observations confirm our initial hypothesis and corroborate the work of Boukari et al. (2008), who had anticipated that continuous pumping beyond the critical flow rate would cause a restructuring of flow lines and a decrease in the productivity of structures in the Godomey sector.

The critical flow rate increased in 2001, demonstrating the initial potential of a virtually untapped or under-exploited reservoir. Currently, the reduction in this specific productivity to 70.9 m³ / h shows that the extraction rate is approaching hydrodynamic breaking points, thus validating the idea that the aquifer is under hydraulic stress.
The application of the water table fluctuation method (WTF) and Turc's empirical 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 medium sand lithology of Continental Terminal and retained by Boukari et al after their work in 2004, the analysis highlighted a remarkable mismatch between meteorological inputs and daily exploitation.

Natural recharge of the Continental Terminal in the coastal sedimentary basin depends on direct infiltration of groundwater withdrawals. However, ESPERE modeling results indicate significant interannual variability in effective rainfall, heavily influenced by actual evapotranspiration (ETR), which consumes the majority of the raw water withdrawals. Given this fluctuating and limited natural recharge, the volume of water pumped by SONEB from the Godomey and Ouèdo fields shows a linear upward trend from 2011 to 2025.

This situation leads to a cumulative water balance deficit, confirming our second hypothesis. As Scanlon et al. (2006) point out, in intensively exploited aquifer systems, artificial discharge through pumping eventually exceeds the " sustainable yield," forcing the aquifer to draw on its historical reserves. In studies conducted in southern Benin, Toutou et al. (2019) demonstrated that the Continental Terminal aquifer is experiencing a progressive depletion of its static reserve due to the fact that withdrawal rates at Godomey exceed the diffuse recharge capacity calculated using the Turc and Thornthwaite formulas by more than 30%. This prolonged piezometric deficit creates an inverted hydraulic gradient, thus increasing the risk of saltwater intrusion via a marine wedge or percolation of polluted surface water from Lake Nokoué or the surrounding marshy areas. This observation is particularly noticeable in the case of the F11 forage field, abandoned due to saltwater intrusion, and could be felt in other forage fields, especially those with high yields, such as the F14 forage field in Godomey and the F9 forage field in Ouèdo.

Analysis of data from the National Institute of Statistics and Demography (INSTAD) from 2011 to 2025 reveals a mathematical correlation between the population explosion in Cotonou (primarily supplied by water pumped from the Godomey and Ouèdo catchment fields) and the increase in water volumes extracted. The linear regression line calculated for population growth almost perfectly matches that of the growth in pumped volumes. The municipality of Cotonou, although a major economic center, sits atop a highly vulnerable and unhealthy shallow aquifer (marshy formations prone to anthropogenic pollution). Consequently, SONEB has historically been forced to relocate its production facilities to the north of the municipality (first the Godomey fields, then more recently Ouèdo) to tap into the captive aquifer of the Continental Terminal, which is of better quality. This rapidly growing population pressure leads to an extraction rate that disregards the aquifer's renewal cycles. Our findings validate the third hypothesis and align with the analyses of Sintondji et al. (2017) on the security of drinking water supply in the coastal region of Benin. These authors established that the rapid and uncontrolled urbanization of the coastal strip is accompanied by soil sealing, which simultaneously reduces the infiltration area (decreased effective recharge) while multiplying the per capita water demand. The Ouèdo catchment area, although inaugurated more recently to replace that of Godomey, is already following the same trend of overexploitation in the face of the growing needs of the population, illustrating the urgency of adopting integrated resource management.

Ultimately, the impact of the pumping regime on the recharge balance is not limited to a simple lowering of piezometric levels; it induces a hydrodynamic transformation of the Continental Terminal aquifer. Intensive pumping acts as a powerful artificial discharge well, disrupting the initial natural hydrodynamic equilibrium (recharge = natural discharge towards outlets). By altering transmissivity and causing the aquifer to become unconfined, the current pumping regime impairs the aquifer's resilience to future droughts. If current demographic trends and extraction rates, as projected by our regression lines, continue, the Continental Terminal aquifer in southern Benin will be exposed to critical reservoir depletion and the depletion of the shallowest wells.

Conclusion:-

This study evaluated the impact of intensive groundwater abstraction on the water-budget equilibrium and hydrodynamic behavior of the Continental Terminal aquifer within the Godomey and Ouèdo wellfields, which constitute the primary drinking water supply sources for the Greater Cotonou area. Based on the hydrogeological investigations, several key conclusions can be drawn with respect to the research objectives.

First, the re-evaluation of pumping-test interpretations reveals significant spatial and temporal variations in calculated hydrodynamic parameters. Apparent transmissivity values ranging from $7.97 \times 10^{-3}\ \mathrm{m}^2/\mathrm{s}$ to $2.22 \times 10^{-3}\ \mathrm{m}^2/\mathrm{s}$ reflect local lithological heterogeneities and varying stress levels during individual tests rather than a uniform regional degradation of the aquifer matrix. Corrections applied to initial storage estimates demonstrate that the storage coefficient values fluctuate between 10^{-4} and 2.33×10^{-3}, characteristic of a semi-confined to localized unconfined system. These findings suggest localized desaturation of the sandy formation in proximity to intensive pumping centers under heavy continuous drawdown.

Second, the water-budget estimation conducted via the ESPERE code (utilizing the Water Table Fluctuation method) revealed a persistent imbalance between diffuse natural recharge (effective precipitation ranging from 50.5 mm/year to 248.1 mm/year) and total groundwater abstractions ($17.2 \times 10^6\ \mathrm{m}^3$/year). The cumulative volume deficit indicates that localized abstraction rates exceed annual effective recharge, thereby inducing long-term storage depletion.

Third, statistical analysis confirmed a strong positive correlation ($R^2 = 0.91$, $p < 0.001$) between demographic growth in the municipality of Abomey-Calavi and increasing pumping volumes. However, water consumption is also governed by structural drivers, including network leakage rates, per-capita consumption shifts, and infrastructure expansion.

Based on the quantitative findings and associated hydrogeological uncertainties, the following management and research strategies are recommended: -

- Site-Specific Management of Wellfields: Differentiate operational management strategies between the Godomey and Ouèdo wellfields instead of treating them collectively, taking into account their distinct pumping rates, hydrogeological boundaries, and local drawdown responses.
- Automated Piezometric and Hydrochemical Monitoring Network: Deploy real-time pressure transducers and continuous electrical conductivity sensors across both wellfields to accurately track long-term water-table trends and establish an early-warning monitoring system against potential saline intrusion from Lake Nokoué and coastal interfaces.
- Numerical Groundwater Flow Modeling: Transition from point-based analytical solutions (e.g., Theis) to a three-dimensional numerical groundwater flow model (such as MODFLOW). This will allow for the explicit integration of aquifer heterogeneities, dynamic boundary conditions, and spatial recharge variability to refine long-term water budgets.
- Standardization of Pumping-Test Protocols and Field Calibration: Conduct standardized, long-duration pumping tests using observation wells to obtain reliable transmissivity and storage values that confirm the effective porosity parameters through site-specific laboratory core analyses or tracer tests.
- Spatial Redistribution of Pumping Infrastructure: Reconfigure and expand the spatial distribution of abstraction boreholes across the Allada plateau to reduce individual pumping rates, minimize localized drawdown cones, and mitigate concentrated hydraulic stress on the aquifer.
- Managed Aquifer Recharge (MAR) Feasibility Assessment: Perform comprehensive hydrogeological and hydrochemical feasibility studies on the Allada plateau to evaluate MAR using captured surface runoff, addressing infiltration capacity, water quality, and clogging risks.
- Harmonization of Historical Datasets and Climate Integration: Standardize historical observation periods across all datasets and integrate climate variability factors into future recharge models to account for seasonal and multi-year precipitation shifts.

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