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SIMPLIFIED MODEL OF REGIONAL FLOWS IN THE LOWER AND MIDDLE OUEME VALLEY IN BENIN

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ABSTRACT

Models of geothermal reservoirs, essential tools for estimating resources, simulating subsurface behavior, and optimizing heat exploitation, have been developed by several researchers. Pressure and temperature data have been determined for the Hêtin-Sota geothermal reservoir, but regional flow data are still lacking. This article has enabled the development of a simplified model of the Hêtin-Sota geothermal reservoir. The objective of this study is to understand the regional flow dynamics in the large-scale underground reservoir (aquifer), i.e. to map the flow directions, in order to improve the management of groundwater resources in the Lower and Middle Ouémé Valley, to which the locality of Hêtin-Sota belongs. The natural regional flow of the Hêtin-Sota geothermal reservoir aquifer was assessed using piezometric, groundwater depth, and borehole depth maps of the Benin coastal sedimentary basin. This map, extracted from the aquifers of the Benin coastal sedimentary basin, was produced in 2024 by Benin Water Directorate (DGEau). The average depth of the static level, that is, the depth of the water measured from the ground surface, is estimated to be less than 10 m. The hydraulic gradient, which is the decrease in hydraulic head (total energy) per unit length in the direction of water flow, was estimated at approximately 0.2%, graphically derived from the piezometric map extract. Mapping the depth of the reservoir in this basin, based on iso-depth curves, indicates that the Cretaceous sand aquifer of the hydrogeological unit to which Hêtin-Sôta belongs is located at a depth of approximately 400 m. This limit value confirms the depth of the Hêtin-Sôta artesian thermal well, which is 417 m. The piezometric map, which presents a reserve of water contained in the pores of saturated aquifer rocks, located below the surface of the Hêtin-Sota aquifer allowed for the representation of aquifer flow at the regional scale but not at the local scale of the study area. Thus, four (04) radiating directions (A, B, C and D) were identified, confirming the phenomenon of radial flow towards the study area. These directions indicate a radial flow from the recharge zone (high loads: 70 m) towards the depressions (low loads: 5 m), favoring high flow rates at the boreholes, confirmed by the artesian and thermal borehole of Hêtin-Sota delivering a flow rate of 60.16 m^3/h before heading towards the bed of the Ouémé river.

The hypothesis of relatively homogeneous regional flows of low amplitude, characteristic of the Hêtin-Sota reservoir alone, appears too restrictive. These results, which are currently partial, serve both as support for and as a constraint on the flow model because of the variation in water temperature which induces convection flows, which do not follow the pressure gradient in a simple way, given that it is a geothermal reservoir (water temperature at the top of the borehole of 53°C and above 30°C).

Keywords: Modeling, hydraulic potential, porous reservoir, Hêtin-Sota, Benin.

INTRODUCTION

Land and water are the most essential natural resources because the entire life system depends on them. Proper management is necessary to achieve maximum utilization (Verma et al., 2022). Benin, a country located in West Africa, has positive thermal anomalies in its subsoil. This is the case with the Hêtin-Sota hot spring, discovered in 1956 following a drilling operation carried out by a Canadian mission that had traveled to the area for earthwork, specifically to extract materials. Having observed the lack of drinking water in the area, the Canadian mission decided to drill a well there. The water from the Hêtin-Sota geothermal reservoir extracted through this well is precious and vital, as temperature is a physical parameter of great importance in water resource management (Boutoutaou et al., 2020; Sourogou et al., 2021; Mezenner et al., 2022; Chow and Teo, 2023; Mehta et al., 2023; Verma et al., 2023; Trivedi and Suryanarayana, 2023; Shaikh et al., 2024; Panchal and Suryanarayana, 2025). It is one of the natural resources characterized by two essential aspects: quantity and quality (Ouis, 2012; Laghzal and Salmoun, 2014; Bouchemal and Achour, 2015; Mohamad et al., 2024) and is available in limited quantities. Unlike other resources, it is extremely difficult to determine its true value (UNESCO Report, 2021). Benin possesses significant water resources distributed across four (04) transboundary basins, the largest of which is the Ouémé Basin. The latter is subdivided into four (04) other sub-basins, including the Lower and Middle Ouémé Valley. The Lower and Middle Ouémé Valley has a very gentle slope of 5 meters over 85 kilometers (Séidou et al., 2021) and is subject to the effects of climate hazards that could negatively impact the water resource and, consequently, the local populations (Séidou et al., 2021). Over the past few decades, climate has been a crucial environmental factor influencing the hydrological behavior of groundwater reservoir watersheds worldwide. Therefore, it is important to incorporate climate change projections into reservoir hydrological modeling to improve water resource management and adaptation strategies in regions facing climate-induced hydrological changes. Thus, assessing future temperatures and precipitation is essential for managing water resources, mitigating the impact of natural disasters, and expanding agricultural opportunities.

The Hêtin-Sota hot spring located in the Lower and Middle Ouémé Valley was rehabilitated in 1990, but about twenty years ago, the main valve at the wellhead and some of the standpipes in this drinking water network were damaged. Since then, there has been a lack of control over the artesian flow gushing from the well. This phenomenon poses a challenge to the management of the reservoir in this locality, which plays a significant role in water resource use (Mehta et al., 2023). It is one of the major reservoirs in the Ouémé Valley in Benin, ranked as the second richest valley in the world after the Nile in Egypt (Hounkanrin, 2015). This reservoir therefore plays a crucial role in water resource management for agricultural irrigation, drinking water supply, and flood protection in the locality, as projections of domestic water demand, based on future population and irrigation needs, clearly indicate significant annual increases(Mehta et al., 2023).

This continuous water flow at the drilling site, could impact the regional flow of the groundwater in the Hêtin-Sota geothermal reservoir. Regional flow refers to the slow, large-scale movement of water within a geological reservoir (aquifer), from recharge zones (high groundwater levels, outcrops) to outlets (low groundwater levels, rivers). Driven by gravity and the permeability of the surrounding environment, this flow is characterized by piezometry (follows groundwater levels) and typically occurs over hundreds of meters to kilometers, at speeds much lower than those of streams. Since the Hêtin-Sota geothermal reservoir is located in a coastal sedimentary basin, the regional groundwater flow within the basin is generally horizontal and directed from recharge zones towards the ocean (outlet). It takes place in porous aquifers (sands, limestones) under pressure in confined zones, with slow speeds, influenced by gravity and geological structure (faults, inclination). The lack of comprehensive analyses of the distribution of natural regional flows in the Hêtin-Sota geothermal reservoir has always been problematic due to insufficient information regarding the static pressure distribution of the reservoir. This is especially true since long-term historical data and their interpretation are crucial aspects for understanding any variation resulting from changes in environmental behavior (Sahu et al., 2024). In the Hêtin-Sota reservoir, geothermal drilling since 1956 has yielded some information on flow rate, depth, and lithology. Using piezometric, water depth, and borehole depth maps available for the coastal sedimentary basin of Benin, at the level of the General Directorate of Water (DGEau), this information allowed for the determination of the natural flow directions of the geothermal fluid at the regional scale. Knowledge of these flow directions should allow for better guidance of future geothermal drilling. The reasons cited above justify the validity of the present study entitled "Modeling of the Hêtin-Sota geothermal reservoir in Benin".

This study aims to understand the regional flow dynamics in the large-scale underground reservoir (aquifer), specifically to map flow directions, in order to improve groundwater resource management in the Lower and Middle Ouémé Valley, which includes the locality of Hêtin-Sota, since the integration of advanced geospatial technologies into reservoir studies improves data-driven decision-making, monitoring efficiency, and contributes to sustainable reservoir exploitation in a changing environmental context. It is justified by the fact that the Lower and Middle Ouémé Valley is subject to the effects of climatic hazards that could negatively impact the resource and, consequently, the population. Therefore, it is necessary to update knowledge for the siting of new boreholes to ensure the sustainability and flow rate of these structures. The study relies on geological, piezometric, and water depth (static level) data to map flow directions. It uses relatively recent data, unlike previous studies that lack recent data or focus on scales that are too small (non-regional).

STUDY AND AREA DATA COLLECTION

The study site is located in the village of Hêtin-Sota, in the Késsounou district of the Dangbo municipality. The Dangbo municipality is located in the Ouémé Department and lies between 6°32’ and 6°39’ north latitude and between 2°28’ and 2°34’ east longitude. Covering an area of 149 km^2, it is bordered to the north by the municipality of Adjohoun, to the south by the municipality of Aguégués, to the east by the municipality of Akpro-Missérété, and to the west by the municipality of Sô-Ava. Administratively, the municipality of Dangbo is divided into seven (7) districts comprising fifty (50) administrative villages. The district of Késsounou includes six (6) villages, one of which is Hêtin-Sota. The village of Hêtin-Sota is bordered to the north by the village of Dèwèmè-Daho (Houédomey district), to the south by the village of Hêtin-Gléhoué (Késsounou district), to the east by the village of Tovè (Dangbo district), and to the west by the Ouémé River. The Hêtin-Sota geothermal well is located along the embankment-access road to the village and at the entrance to the settlement. The geographic coordinates of the well are : 2.50396 E and 6.58789 N. The site housing the well is located on the left bank of the Ouémé River, 190 meters from it. Fig. 1 shows the geographic location of the Hêti-Sôta geothermal well in the municipality of Dangbo, Benin.

From a hydrogeological perspective, Hêtin-Sota has a continuous aquifer with interstitial porosity and several resources, the most important of which are sands, which constitute the continuous aquifers of sedimentary regions. This aquifer contains significantly greater hydrogeological resources and is generally easier to prospect than those of the basement or older cover deposits, even though these resources are not yet fully quantified. It is a single-layer aquifer of Upper Cretaceous sands (Turonian-Coniacian), a confined water table beneath Senonian and Maastrichtian clays and marls, where it deepens rapidly, making its exploitation uncertain. Fig. 2 shows an excerpt from the hydrogeological map of the coastal sedimentary basin of Benin, locating Hêtin-Sota.

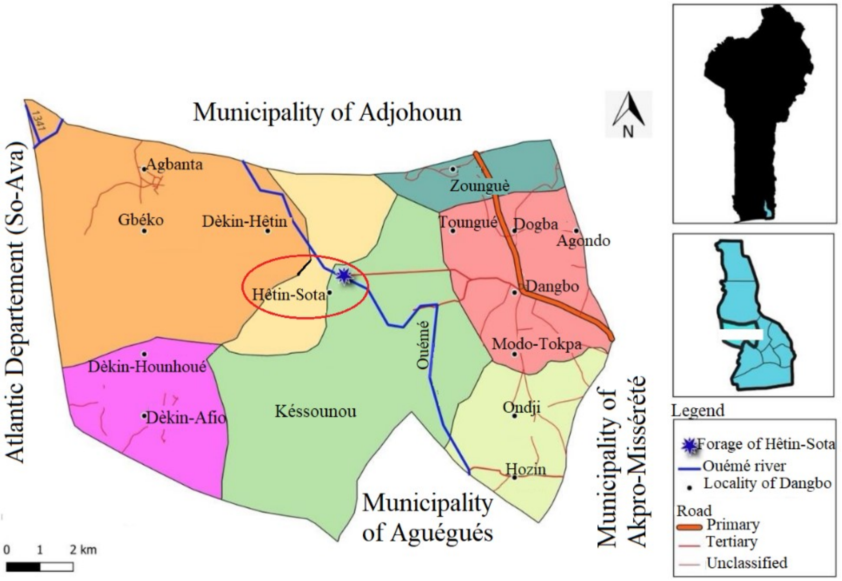

Figure 1: Geographical location of the Hêtin-Sota artesian and thermal well in the municipality of Dangbo (IGN, 2024)

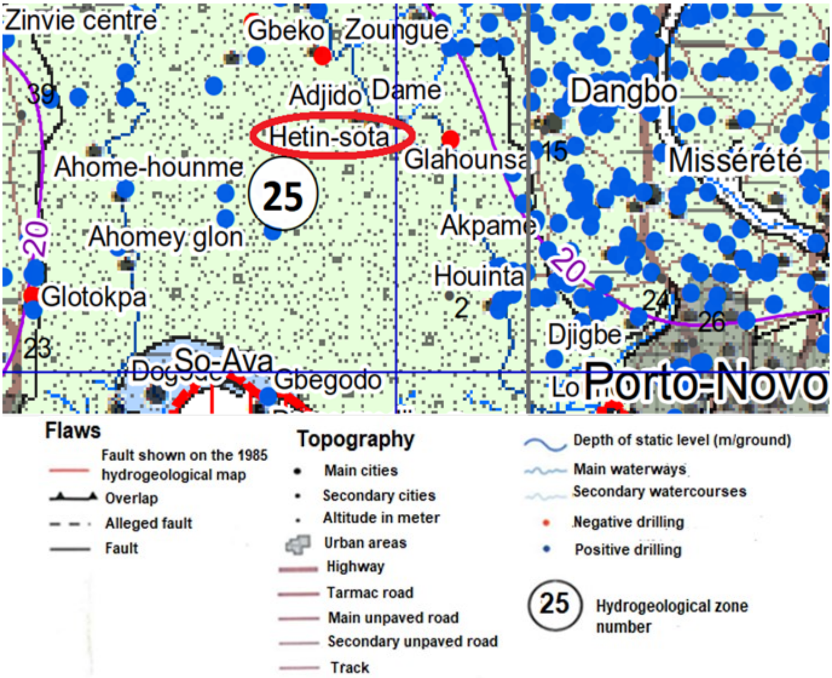

Figure 2: Extract from the hydrogeological map of the coastal sedimentary basin of Benin locating Hêtin-Sota (DGEau, 2024)

According to information received from the DGEau (Directorate General of Water), Hêtin-Sota is located in the coastal sedimentary basin and belongs to hydrogeological unit 25, which corresponds primarily to a Quaternary aquifer composed of recent alluvium and ancient terraces of the Ouémé, Mono, and Couffo depressions: sand, clay, gravel, and coal-bearing layers. This formation is characterized by a confined aquifer, protected by layers of Senonian and Maastrichtian clays and marls, deepening towards the south. Fig. 3 shows the hydrogeological units of the coastal sedimentary basin and the village of Hêtin-Sota, located within hydrogeological unit 25.

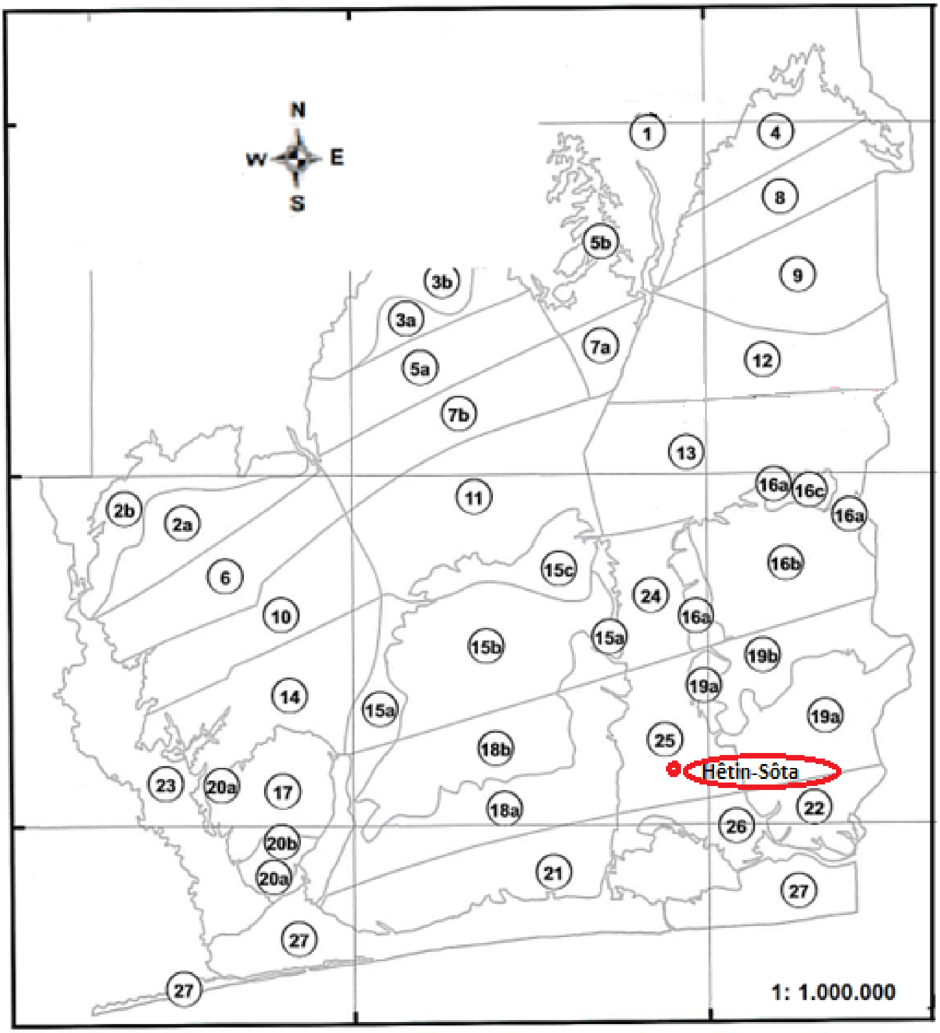

Figure 3: Hydrogeological units of the coastal sedimentary basin locating the Hêtin-Sota geothermal reservoir (DGEau, 2024)

Data concerning the geometry and hydrodynamics of the artesian and thermal borehole are summarized in Table 1 and mainly concern technical data from the artesian and thermal borehole drilled in the village of Hêtin-Sota, provided by the Benin Water Authority (DGEau, 2024). This Table indicates that the water temperature at the top of the artesian and thermal borehole in Hêtin-Sota is 53°C, therefore between 30°C and 100°C, and the borehole depth is 417 m, between 400 and 2000 m, thus at the level of the reservoir in the locality of Hêtin-Sota, we have medium and low energy geothermal energy (Zerrouki, 2007).

Table 1: Geometric characteristics and hydrodynamic parameters of the Hêtin-Sota artesian and thermal well (DGEau, 2024).

Drilling depth H (m)	417
Roof depth (m)	392
Thickness of the reservoir e_{res} (m)	25
Drill hole diameter D (m)	0.200
Flow rate Q (m^3/h)	60.16
Permeability (m/s)	10^{-5}
Acceleration of gravity g (m/s^2 or N/kg)	9.81
Fluid temperature at the ground surface (°C)	53

The different horizons of the drilling profile are presented in Table 2. This Table indicates that at a depth of 392 m, there is calcareous clay and sandy marl, corresponding to the reservoir roof, and the reservoir wall, which is at 417 m. This allows us to determine the reservoir thickness to be 25 m (417 m - 392 m). This confirms the reservoir thickness value given in Table 1.

Table 2: Profile of the Hêtin-Sota thermal borehole (DGEau, 2024).

Upper depth (m)	Minimum depth (m)	Lithology	Description
0	47	Clay	Clay
47	75	Fine sand	Fine sand interbedded with sandy clay
75	104	Clay sand	Clay sand + fine sand + loamy sand
104	284	Clay	Clay + clayey sand loam
284	288	Clay	Gray-blue clay
288	298	Marne	Dark sandstone and blackish gray
298	368	Clay	Layered gray clay
368	392	Limestone	Calcareous clay and sandy loam
392	398	Limestone	Marble and white limestone
398	417	Lmestone	Cracked whitish shell limestone

METHODOLOGY AND MODEL DEVELOPMENT

This study aims to quantify the velocity associated with variations in temperature and pressure that affect the density involved in the expression of the hydraulic potential. The hydraulic potential, the main driving force of the flow in the Darcy hypothesis, comprises a first term related to reservoir pressure and a second term that is a function of the position of the particle in question, measured relative to a common reference (generally sea level).

In this case, it is this second term that creates difficulties, because the Z position is multiplied by the density, which varies locally. When the density cannot be considered constant, solving the actual problem requires examining two points in detail:

- the definition of hydraulic potential, from which velocity is derived in the classical isodensity Darcy formulation,
- the flow law, that is to say the relationship between causes and effects or in other words, the correlation matrix between forces and generalized flows.

Among the generalized forces that generate the overall flow (flux), the assumption of constant density leads to the identification of two classical forces, respectively related to pressure energy and potential energy. In this case, velocity is derived from a scalar potential: the hydraulic head. When a variable density is present, a third generalized force related to density phenomena is added. Indeed, it is known, both intuitively and practically, that less dense water tends to migrate towards higher areas, while denser water flows towards lower points. In this significantly more complex case, topography plays a determining role because the geometry of the corresponding streamlines is no longer governed by the head gradient but by the concept of the line of steepest descent on the topographic surface. The magnitude of this velocity component is then directly related to the sign of the dip of the reservoir layer.

Regarding the definition of potential, it is worth recalling that there are four (4) classic concepts. Consider an aquifer for which the fluid density is solely a function of the elevation Z. By determining the pressure that would be measured at the reference level in a well tapping the reservoir, this pressure can then be converted into a water column height of a fixed density. The use of these levels, the definitions of which will be reviewed later, allows for the comparison of the flow drivers between different points in the aquifer.

With the following conventions:

P_g : Measured reservoir pressure;

Z_g : Pressure measurement rating;

Z_r : Reference dimension;

P_r : Reference dimension pressure;

ρ_g : Reservoir fluid density;

ρ_d : Density unit of fresh water;

We then define the four (04) level concepts, (Chiarelli A.,1973; Vandenbeush M., 1976 and Rojas J., 1989):

- -Potentiometric level HP

$$HP = \frac{P_g + \int_{Z_r}^{Z_g} \rho(Z) g dZ}{\rho_d g} \tag{1}$$

It represents the total energy of the water, corresponding to the level at which the water stabilizes in the piezometer. It is the sum of the potential charge and the pressure charge. In this case, we take into account the variable density $\rho(Z)$ between the reservoir Z_g and the reference elevation *Z*r.

- Pseudo-potentiometric level HPP

$$HPP = \frac{P_g}{\rho_d g} + (Z_g - Z_r) \tag{2}$$

This refers to the height of a theoretical freshwater column that would equalize the layer pressure (hydrostatic pressure) at a given point in the reservoir, particularly when the formation water has a different density than the freshwater. We assume here that the density is equal to unity between the points with elevation Z_g and Z_r

- Piezometric level HPZ

$$HPZ = \frac{P_g}{\rho_g g} + (Z_g - Z_r) \tag{3}$$

It describes the height to which water rises in a pipe submerged in the water table, representing the water pressure. It is the sum of the altitude of the measurement point and the pressure height. In this case, the entire fluid column of the borehole has a constant density equal to that of the reservoir.

- Pseudo-piezometric level HPPZ

$$HPPZ = \frac{P_g}{\rho_d g} + (Z_g - Z_r) + \frac{\rho_g}{\rho_d} \tag{4}$$

The pressure calculated at the reference elevation is converted into a freshwater column height.

In fact, and in practice, none of these four definitions corresponds to the true potential. One reason is the basic assumption that the density depends only on the elevation Z. Nevertheless, to obtain a regional flow estimate, and taking into account the average density value, which is very close to unity, the classical hydrogeological approach with constant density was initially used. The combined use of the piezometric map and the groundwater depth map (surface area map or isobath map) is the fundamental methodological approach used in this work to map regional flows. It has made it possible to reconcile the physical dynamics of water with the practical management of the resource.

The piezometric map is a representation of the aquifer surface using isopiestic lines (lines of equal water elevation). It allows visualization of the direction of groundwater flow, which occurs perpendicularly to the isopiestic lines, from high potential (high elevations) to low potential (low elevations). It also allows the determination of the hydraulic gradient. The spacing between the curves indicates the intensity of the hydraulic gradient. Closely spaced curves indicate a strong gradient (rapid flow), while widely spaced curves indicate a weak gradient. It also allows for the identification of boundaries, that is, the location of piezometric peaks (groundwater divides), recharge zones (high groundwater levels), and discharge zones (rivers, springs, seas).

The water depth map is crucial for resource management and vulnerability assessment. Also known as an isobath map, it indicates the distance between the ground surface and the piezometric surface. It identifies areas where the water table is very close to the surface, indicating high vulnerability to pollution or outcropping (risk of groundwater seepage). It allows for determining the drilling depth required to reach the water table and assessing pumping costs. Unlike piezometrics, which provides elevation, it shows the water table's position relative to the local topography, essential for development projects (basement depths, foundations, agricultural drainage). The combined analysis of these two maps provides a three-dimensional view of the aquifer system. In summary, piezometry structures the flow pattern, while the water depth map defines the management and vulnerability of the resource.

- Hydraulic gradient

This is calculated by placing two piezometers L meters apart. The gradient is the ratio between the difference in level ($\Delta h = H1 - H2$) between the piezometers and the distance L (Fig. 4). In the present study, a piezometric map was used, measuring the distance between two isopiezometric curves and then measuring the distance (hydroisohypses) between them.

The hydraulic gradient (i) is calculated by:

$$i = \frac{H1 - H2}{L} \quad (5)$$

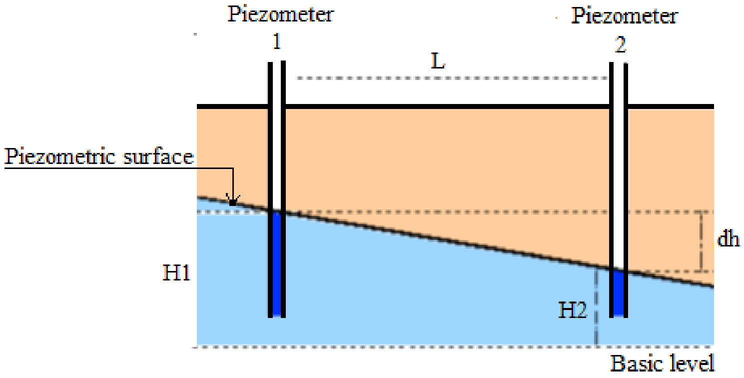

Figure 4: Calculation of the hydraulic gradient with two piezometers

RESULTS AND DISCUSSIONS

Analysis of boreholes located in the coastal sedimentary basin of Benin allowed for the mapping of the reservoir depth (Fig. 5) of this basin. These depths are measured relative to sea level. This map, based on the iso-depth curves, shows that the Cretaceous sand aquifer of hydrogeological unit 25, to which Hêtin-Sota belongs, is located at a depth of approximately 400 m. This depth limit confirms the depth of the Hêtin-Sota artesian thermal borehole, which is 417 m.

The spatial distribution of the corresponding piezometric level HPZ is shown in Fig. 6.

The piezometric map (Fig. 6) was created from data collected from piezometers distributed throughout the coastal sedimentary basin. This map shows, based on piezometric curves, that there are several regional water flow directions in the Lower and Middle Ouémé Valley, to which Hêtin-Sota belongs.

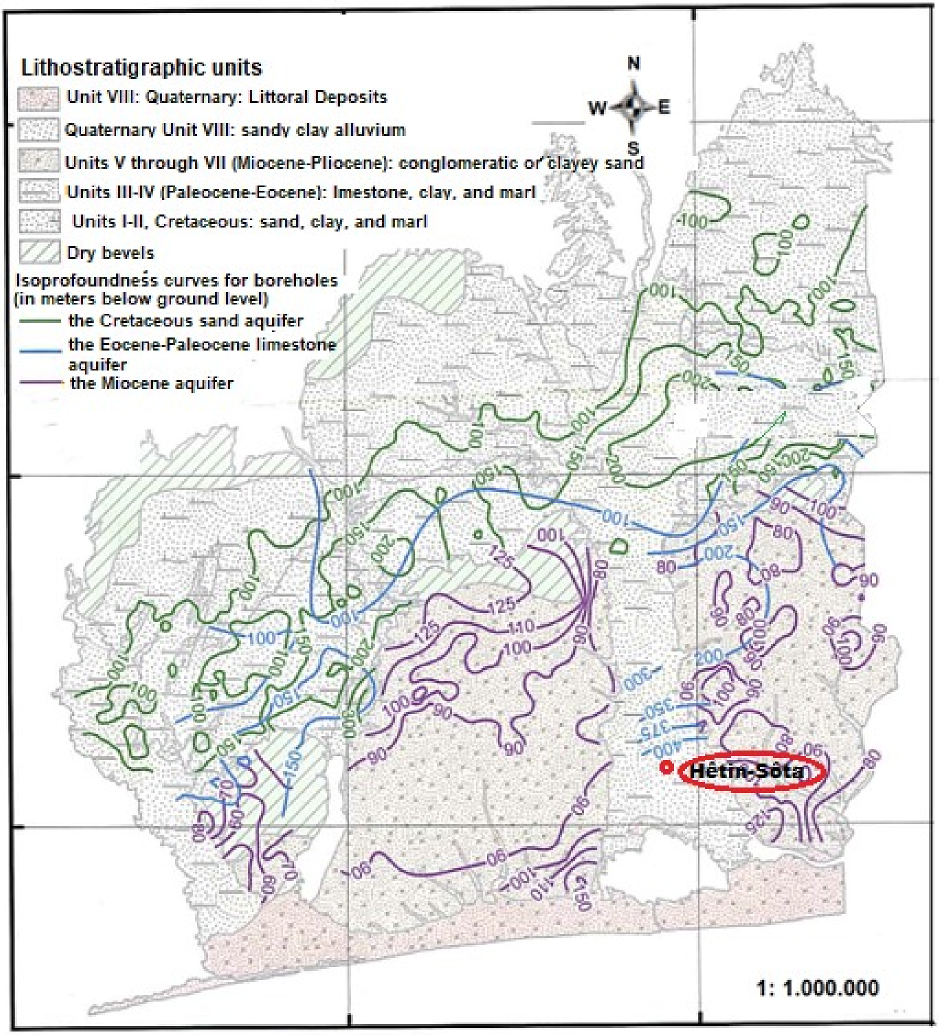

Figure 5: Aquifers tapped and borehole depth contours in the coastal sedimentary basin locating the Hêtin-Sota geothermal reservoir (DGEau, 2024)

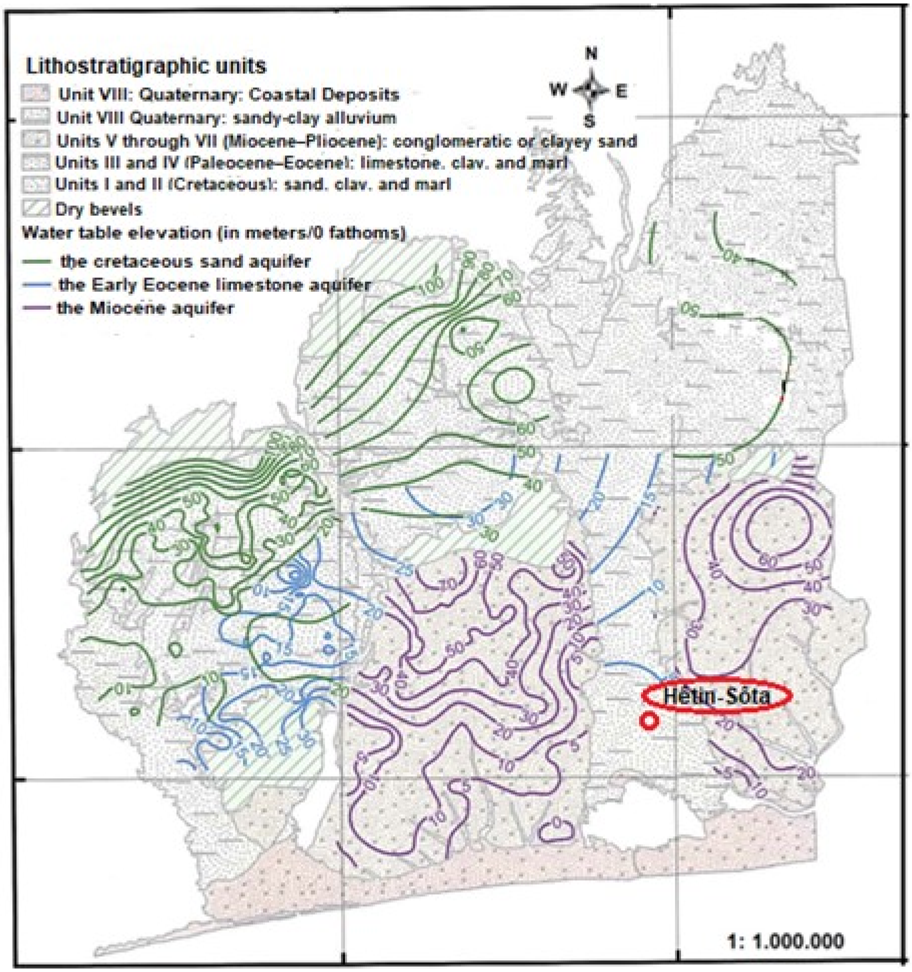

Figure 6: Piezometric map of the coastal sedimentary basin in meters of water column relative to sea level, locating the Hêtin-Sota geothermal reservoir (DGEau, 2024)

In terms of the flow law, and assuming the previous hypothesis, adding the isotropy of the permeability, the fluid trajectories are lines orthogonal to the isovalue curves (Fig. 6). Fig. 6 also shows a spatial variation of approximately ten meters (10 m) and, more importantly, a very homogeneous hydraulic potential. Looking at the phenomena on a regional scale, Fig. 7 shows some of the main flow directions (arrows A, B, C, and D) deduced from Fig. 6. These directions show a radial flow from the recharge zone (high heads: 70 m) towards depressions (low heads: 5 m), favoring high flow rates at the boreholes before flowing towards the Ouémé River bed (Fig. 1). This is confirmed by the Hêtin-Sota artesian and thermal borehole, which delivers a flow rate of 60.16 m^3/h. This map will allow the identification of some areas likely to be recharge zones and potential locations for groundwater storage, suitable for the construction of new hydraulic structures. These results demonstrate a connected reservoir: recharge-storage in depressions-flow towards a river drain, which makes the aquifers vulnerable to chemical pollution, particularly from intensive agriculture with the use of chemical inputs. These results corroborate those of De Lasme et al., (2026). According to these authors, the study of groundwater dynamics in the Sinématiali department (Poro region, northern Côte d'Ivoire) shows, through equipotential lines, a radial flow from the recharge zone (high head: 360 m) towards depressions (low head: 200 m), favoring high flow rates at the boreholes. This is confirmed by boreholes delivering flow rates greater than or equal to 5 m^3/h.

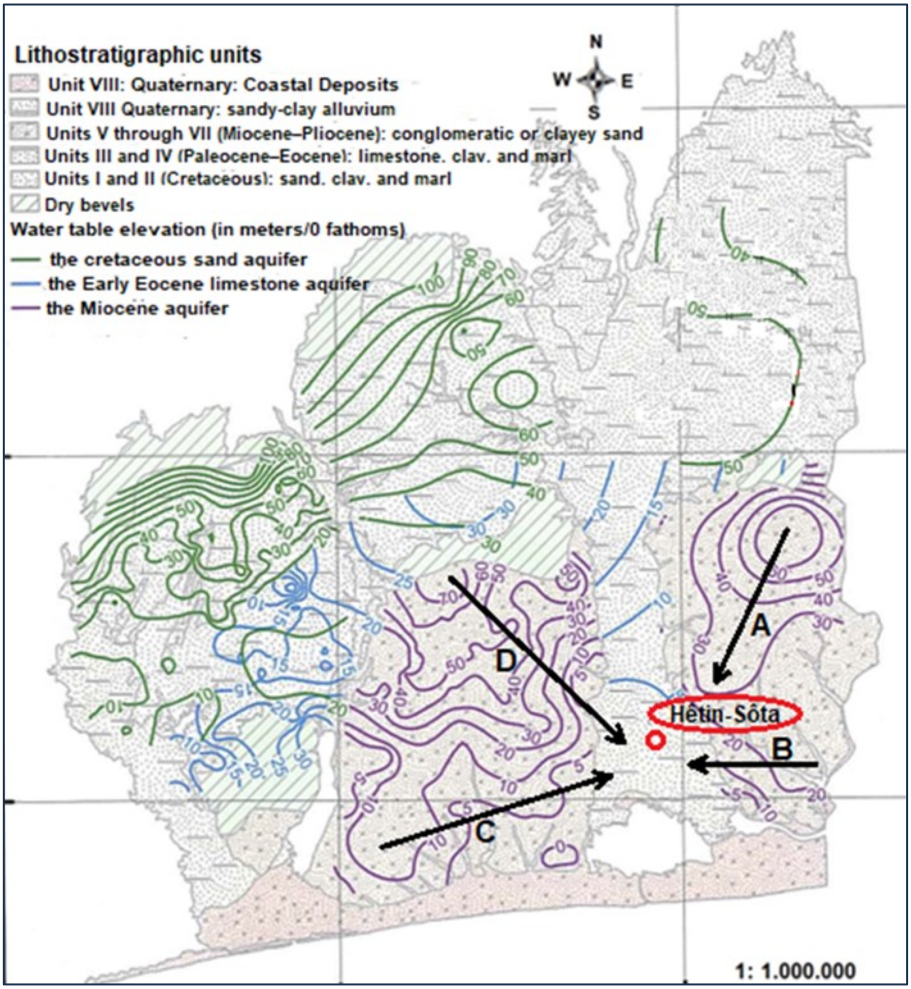

Figure 7: Map of the main regional flow directions (A, B, C and D) of the Hêtin-Sota geothermal reservoir (DGEau, 2024)

CONCLUSIONS

Regional flow in the Hêtin-Sota geothermal reservoir is weak, and its amplitude can be locally amplified by variations in topography or density, which could explain a number of observed anomalies. Accounting for these disruptive effects requires a detailed analysis of the often-complex interaction between hydrodynamic, thermal, and chemical variables. In this context, the consistency of the distributions of the different parameters is the primary condition for validating the synthetic model of the Hêtin-Sota geothermal reservoir.

The heterogeneous model would be more complex, or closer to reality, in terms of the physical laws introduced to describe the reservoir's behavior (for example, by accounting for diffusion or dispersion within the reservoir).

Furthermore, the isopiestic lines drawn are based on groundwater level values from 2024 and are more representative of the current situation. In particular, it has been observed that the piezometric level of the Hêtin-Sota aquifer has changed since 2024 due to the lack of industrialization in the area. The piezometric model used remains schematic given the small number of measurement points considered to define the aquifer flow: direction and hydraulic gradient. It is recommended that, based on point and synchronous measurements within the study area, regional piezometric data be confirmed, a piezometric map be created at the local scale, and the hydraulic gradient be determined.

In summary, the hypothesis of relatively homogeneous, low-amplitude regional flows characteristic of the Hêtin-Sota reservoir appears too restrictive. These results, currently partial, both support and constrain the flow model. The heterogeneous model, which is both more complex and more precise, appears to be a desirable complement to the homogeneous model studied in this work.

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