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Hydrogeological, Geotechnical, and Geophysical characterizations for the Establishment of a Fecal Sludge Treatment Plant: Case of Agadez City, Northern of Niger

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Abstract: The management of faecal sludge is a major public health and environmental protection issue, particularly in Sahelian towns lacking suitable infrastructures. In the city of Agadez, in northern Niger, the absence of a treatment plant accentuates the risks of groundwater pollution, soil degradation and the spread of water-borne diseases. This study aims to assess the technical and environmental feasibility of setting up a sewage sludge treatment plant in Agadez, through hydrogeological, geotechnical, geophysical and topographical investigations. The results highlighted a stable gravelly soil with good bearing capacity and low permeability, a well-protected deep-water table (150 to 245 m), a topography with a natural slope favorable to gravity flow, an available surface area well in excess of requirements and free of litigation, and a location less than 10 km from the center of the sewage sludge activity. The multi-criteria analysis confirms that the site meets virtually all technical and regulatory criteria, with the exception of minor water and electricity connection work. The installation of this plant will make sludge collection and treatment safer, reduce health and environmental impacts, and contribute to Niger's sustainable development objectives.

1. Introduction

Sanitation and proper management of fecal sludge are critical global challenges, and Africa faces significant obstacles in this area. In Niger, a West African country, and particularly in the city of Agadez, fecal sludge management represents a critical concern. Global, African, and context-specific statistics for Niger and Agadez highlight the importance and relevance of this study. At the global level, the figures are alarming. According to data from the World Health Organization (WHO) and UNICEF, nearly 4.5 billion people worldwide approximately 60% of the global population do not have access to safely managed sanitation facilities. Moreover, about 892 million people practice open defecation, thereby exposing communities to serious health risks associated with untreated fecal sludge. These figures underscore the urgent need to improve fecal sludge management at the global scale. Fecal sludge management constitutes a major environmental challenge in rapidly growing African cities. In sub-Saharan Africa, where the vast majority of households rely on non-sewered sanitation systems such as pit latrines and septic tanks, the proper desludging and treatment of these wastes are essential to prevent public health and environmental risks. Despite efforts undertaken, many cities suffer from a lack of adequate treatment infrastructure, leading to informal or inadequate management of these liquid wastes (Strande et *al.*, 2014).

In West Africa, this problem is particularly acute. Sewage sludge treatment plants (STBV) are rare, undersized, or sometimes non-functional. The direct discharge of untreated sludge into the environment (surface water, soil, wetlands, etc.) contributes to the degradation of ecosystems, groundwater pollution, and the spread of waterborne diseases (Dodane et *al.*, 2012, Cofie et *al.*, 2009).

The issue of sewage sludge treatment is therefore closely linked to the challenges of urbanization, public health, and natural resource conservation. It requires an integrated approach combining appropriate technology, effective governance, and the involvement of local stakeholders

In line with the Sustainable Development Goals (SDGs) for 2030, Niger has adopted the Water, Hygiene, and Sanitation Sector Program.

Several challenges must be overcome in order to achieve the objectives of PROSEHA's Hygiene and Sanitation Before installing any sewage sludge treatment plant, it is essential to carry out geotechnical, hydrogeological, and geophysical studies to ensure the technical and environmental sustainability of the structure. On the one hand, geotechnical studies make it possible to characterize the bearing capacity and stability of the soil in order to adapt the foundations and structures of the basins, digesters, or lagoons, thus avoiding the risk of subsidence or cracking (Strande et *al.*, 2014, Ong *et al.*, 2017). On the other hand, hydrogeological analysis is essential to prevent groundwater pollution through accidental infiltration or gradual diffusion of untreated wastewater and sludge. Several studies, highlight that many plants in sub-Saharan Africa have failed or caused local pollution because they did not take into account piezometric levels, soil permeability, and aquifer vulnerability (Semiyaga *et al.*,2015, Bassan *et al.*, 2013). In addition, geophysical studies (such as electrical resistivity or seismic imaging) provide complementary data on the structure of subsurface layers, the presence of saturated zones or faults, and the continuity of impermeable layers necessary to ensure effective effluent containment (Rahman *et al.*, 2013, Zongo *et al.*, 2022).

These integrated approaches are now recommended in international guidelines such as those of the World Bank and WHO for urban sanitation projects (World Bank, 2019). In West Africa, feedback from experiences in Dakar (Senegal) and Ouagadougou (Burkina Faso), for example, confirms that the absence of such preliminary studies has led to high rehabilitation costs and avoidable environmental impacts (Strande *et al.*, 2014, Kone *et al.*, 2010).

In Niger, treatment infrastructure is virtually non-existent at the national level, although a few attempts have been made, notably in Niamey and Maradi. The lack of technical resources, monitoring, financing, and a clear regulatory framework limits the sustainability and effectiveness of the few facilities that have been set up. The environmental consequences are serious: water contamination, proliferation of disease vectors, and increased exposure of vulnerable populations to health risks (Kone *et al.*, 2010, GIZ and CREPA, 2010).

In the Agadez region, located in northern Niger, the issue of sewage sludge management is particularly acute. Indeed, sewage sludge treatment plants are virtually non-existent, if not completely absent, even though the urban population and economic activities are growing steadily, particularly around the city of Agadez and in mining areas. This lack of specialized infrastructure poses a serious environmental and health problem for the entire region. In the absence of treatment plants, sludge from septic tanks, latrines, and other non-collective facilities is generally dumped indiscriminately into the environment, on vacant lots, or in natural depressions, without prior treatment. This situation poses several major risks: pollution of shallow groundwater, degradation of soil quality, and the spread of waterborne diseases such as diarrheal infections, cholera, and parasitic diseases (Strande *et al.*, 2014, Cofie *et al.*, 2009). Studies conducted in other Sahelian regions, notably in Niamey and Ouagadougou, have shown that the lack of appropriate treatment facilities is directly correlated with a significant increase in morbidity indicators linked to unsanitary conditions (Dodane *et al.*, 2012, Mbéguéré *et al.*, 2010).

Furthermore, the specific geographical and climatic characteristics of the Agadez region, marked by an arid climate, sandy soils, and increased vulnerability of aquifers, reinforce the need to implement adapted and resilient solutions. Several authors emphasize that in such desert contexts, even the smallest amount of untreated pollutants can lead to long-lasting contamination, particularly due to low dilution and rapid infiltration into groundwater conditions (Semiyaga *et al.*, 2016; World Bank, 2019).

It therefore appears essential, for reasons of public health and natural resource conservation, to plan and implement sewage sludge treatment plants in the Agadez region. This approach should be based on rigorous preliminary studies (geotechnical, hydrogeological, and environmental) to ensure their sustainability and effectiveness, as recommended in the work of conditions (Kone *et al.*, 2010, Rahman *et al.*, 2020).

The construction of a sewage sludge treatment plant in Agadez is now seen as a major necessity in order to address the health and environmental challenges facing the region. Such infrastructure would enable the safe and hygienic collection, treatment, and disposal of sludge, significantly reducing the risk of soil and groundwater pollution and the spread of diseases linked to unsanitary conditions. It would thus contribute to the preservation of water resources, which are essential in this Saharan context, and to the sustainable improvement of the quality of life of the inhabitants of the city of Agadez and its surroundings.

This research article is therefore part of this dynamic, focusing on the hydrogeological, geotechnical, and geophysical studies prior to the establishment of a sewage sludge treatment plant in the city of Agadez. These studies aim to assess the characteristics of the subsoil, the vulnerability of aquifers, and the bearing capacity of soils in order to optimize site selection and limit the environmental and health impacts associated with the future operation of the plant.

2. Methodology

2.1. Presentation of the study area

The Agadez region, located in northern Niger, covers an area of approximately 667,799 km², making it the largest administrative region in the country, representing nearly half of the national territory (INS Niger, 2022). It is characterized by a Saharan desert climate, high temperatures, and very low rainfall, generally less than 100 mm per year (Diori *et al.*, 2018). The region consists of vast sandy plains, rocky areas, and mountain ranges, including the Aïr Mountains, which are listed as a UNESCO World Heritage Site for their ecological and cultural value. Most of the population is concentrated in urban areas such as Agadez, the regional capital, where sanitation challenges are particularly worrying due to the lack of adequate infrastructure for treating sewage sludg (Moussa *et al.*, 2021). The study area is located west of the city of Agadez, in the department of Tchirozérine, approximately 900 kilometers northeast of Niamey, south of the Aïr Mountains, at the mouth of the Irhazer Plain. Its geographical coordinates are: 16° 58′ 00″ North and 7° 59′ 00″ East (**Figure 1**). This strategic location on the outskirts of the city was chosen in order to limit the risk of pollution to inhabited areas and local water resources while remaining accessible to sewage operators.

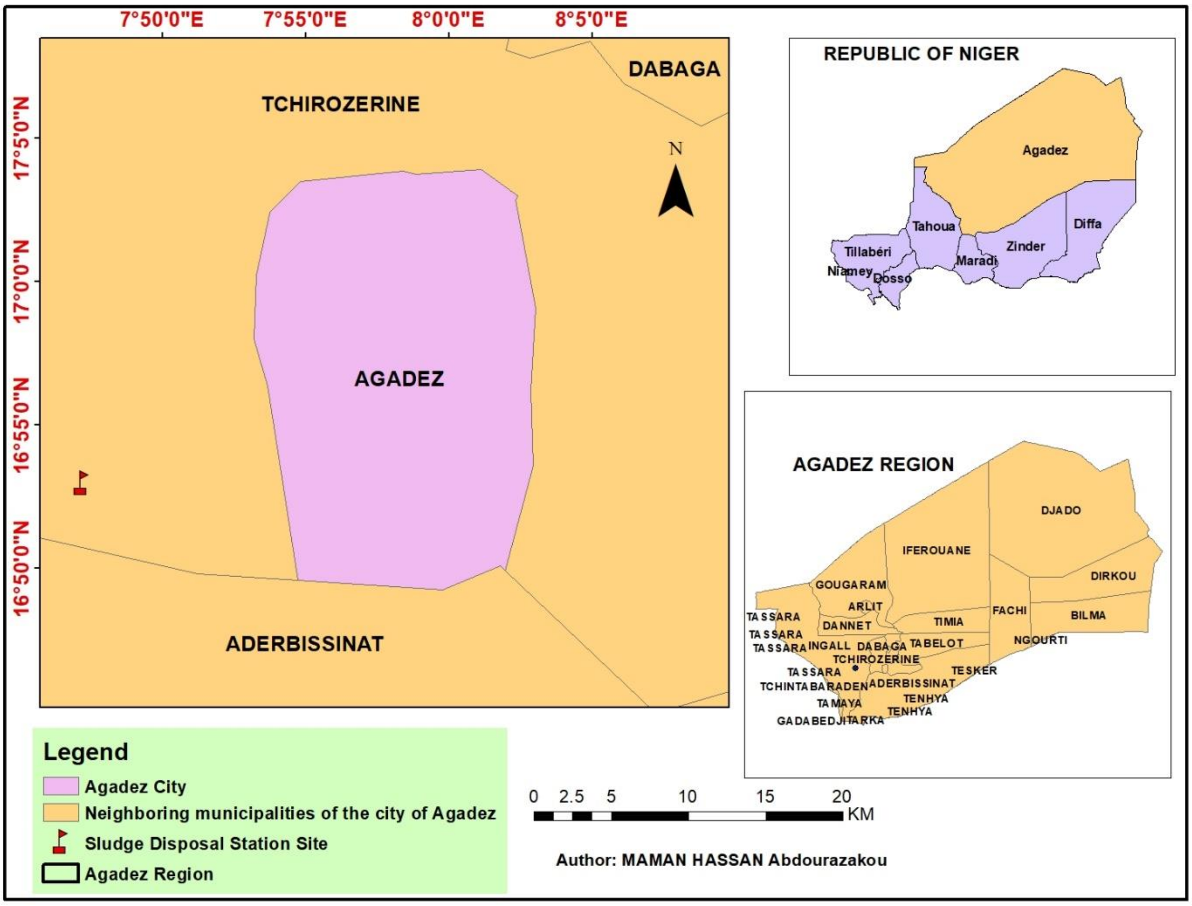

Figure 1. Study area

2.2. Geological Context of the Agadez Region

The municipality of Agadez and its surroundings are geomorphologically characterized by the presence of a vast plateau of ferruginous sandstone, sloping gradually from northeast to southwest (INS Niger, 2022, Diori, 2018). Over time, erosion has shaped this landscape, creating steep-sided valleys, plateaus, steep slopes, glacis, and lowlands. This complex relief is also crossed by two temporary watercourses, the Kori Irhazer Madaran and the Kori Teloua, which play an important hydrological role during the rare rainfall (Moussa *et al.*, 2021).

The geology of the Agadez region is characterized by two distinct major units (**Figure 2**):

- The crystalline basement of the Aïr Massif, located to the east, which forms part of the vast Hoggar mountain range. It is composed of Precambrian crystalline schist formations, associated with granitic intrusions (Greigert *et al.*, 1966, BRGM, 1985).

- ➢ The Tim Mersoi sedimentary basin, extending mainly to the west, which includes formations ranging from the Paleozoic to the Mesozoic, primarily composed of sandstones, shales, and limestones.

From a tectonic and structural perspective, these two geological units have been affected by several major fault systems:

- Dominant orientations of NE, NNE–SSW, and NE–SW, related to ancient tectonic movements.
- **The Arlit Fault** (N–S trend), the main regional fault, which can be traced from south of Agadez to In Azawa in Algeria (Greigert *et al.*, 1966, BRGM, 1985).
- Three main fault systems within the Tim Mersoi Basin:
    - Submeridional faults, such as the Arlit–In Assaouas Fault and the Tchizakaraten Lineament.
    - N30–40 oriented structures, including the Madaouela Flexure, the Adrar-Emoles Flexure, and the Aouderer Ridge.
    - N70–80 oriented faults, including the Ogba Sheaf, the Aguijir Fault, the Mehrérout Fault, and the Azouza Fault.

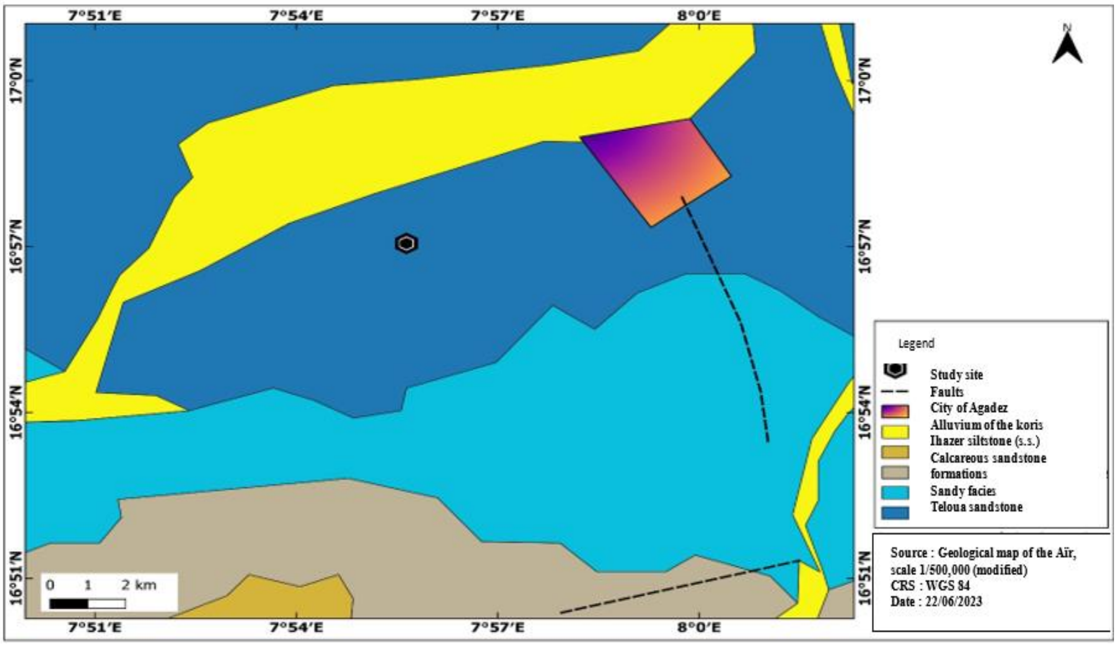

Figure 1. Geological map of the study area

The Agadez region lies within the broader framework of the Iullemmeden Basin, a major hydrogeological system shared among several West African countries. This basin is characterized by extensive geological sequences dating from the Paleozoic, Mesozoic, and Cenozoic eras, forming deep, multilayered, and generally confined aquifers in the central part of the basin (Greigert *et al.*, 1966).

These aquifers play a crucial role in supplying water to local populations, in a Saharan climatic context where surface water resources are scarce and seasonal.

In the Agadez region, four main aquifers have been identified and are currently exploited:

- The Tchirozérine 2 Aquifer, of Jurassic age, composed mainly of sandstone formations. This aquifer is also known to host uranium mineralization, particularly in the Tchirozérine and Arlit areas.

- The Téloua Aquifer, of Triassic to Jurassic age, consisting of sandstones interbedded with clay formations, has strategic importance for supplying water to settlements located west of Agadez.
- The Tarat Aquifer, also of Jurassic age, recognized for its productivity and depth, is used for several industrial and domestic boreholes.
- The Guézouman Aquifer, which complements this system, with similar lithological characteristics and hydraulic behavior.

The hydrogeological entities of the study area are mainly represented by three major types of formations:

- Metamorphic and plutonic formations of the Precambrian basement, generally low in permeability and of limited hydrogeological potential.
- "Nubian sandstone" formations, constituting major aquifer reservoirs within the basin, notably in the Tarat and Guézouman units (CRGM, 2016, IAEA, 2015).
- Detrital formations (sandstones and sands) of the Tim Mersoi sedimentary basin, which play an important role in the dynamics of groundwater flow.

This complex hydrogeological context highlights the necessity of conducting detailed studies prior to establishing any potentially polluting infrastructure, such as faecal sludge treatment plants, in order to preserve both the quality and availability of groundwater resources.

Agadez experiences a hot desert climate, classified as *BWhw* according to the Köppen–Geiger climate classification, characteristic of the Saharo–Sahelian transition zone, which gradually shifts from the arid Sahara to the semi-arid Sahel (Peel *et al.*, 2007). This climate is marked by extreme aridity prevailing for nearly nine months of the year, with average monthly precipitation of less than or equal to 10 mm. The long dry season can be divided into two periods: a very dry and hot season from November to March, and an extremely hot dry season from April to June. In contrast, the rainy season is short, irregular, and generally concentrated between July and August, with peak rainfall occurring in August at around 50 mm (Niger National Meteorology Directorate, 2019). This wet season results mainly from changes in wind regimes linked to the migration of the Intertropical Convergence Zone (ITCZ) (Nicholson, 2013). Mean maximum temperatures in Agadez remain very high throughout the year, peaking at 44–45 °C in June and dropping to 27–28 °C in January. Even during the least hot months, maximum temperatures generally exceed 28 °C, ranking Agadez among the hottest cities in the world (Barry *et al.*, 2018).

2.3. Materials Used for Geological and Geotechnical Studies

The geotechnical investigations required the use of a combination of field equipment and measuring tools suited for soil reconnaissance and the assessment of soil bearing capacity. A total station integrating a theodolite and a surveyor's level was used to carry out altimetric surveys and to accurately position the borehole points. Surveying rods, measuring tapes, and level reading discs were employed to check alignments and elevations. To document field observations, a field notebook was used alongside note-taking on a laptop computer equipped with software such as Excel and Word for data processing and the preparation of measurement tables.

The geological studies were supported by the use of a geological compass and a rock hammer for sample collection and on-site analysis of the encountered formations. The compass was used to record the orientations of geological structures (strata, faults, etc.), which are essential for refining the local geological model. Field observations were systematically recorded in a notebook and documented with a camera. Geological maps and satellite imagery were used both prior to and during the field campaigns to guide itineraries and locate areas of interest. For processing the collected data and producing final maps, Geographic Information System (GIS) software such as ArcGIS, QGIS, and MapSource were employed, complemented by standard office software. Finally, all field operations were conducted in compliance with safety standards, using personal protective equipment adapted to the arid environment and the technical constraints of the region.

2.4. Materials Used for Geophysical Studies

As part of the geophysical studies, particularly for subsurface prospecting and characterization using the electrical resistivity method, several specialized pieces of equipment were deployed. The main device was a geoelectrical instrument coupled with a geoelectric probe, which injects an electrical current into the ground to measure apparent resistivity an essential parameter for modeling geological layers. To ensure proper ground contact, eight steel electrodes and two coils of electrical wire were used to connect the various measurement points. The positioning of geophysical survey profiles was carried out using a differential GPS and a Garmin Map 72S GPS, ensuring optimal accuracy for coordinates and survey grids. For data interpretation, two specialized software packages were employed: Aidu Prospection and Surfer 13, which allow the generation of 2D tomographic subsurface profiles and the estimation of true resistivities of the encountered formations. Satellite imagery from Sentinel-2 and topographic and geological maps were also utilized to complement spatial analysis and enhance understanding of the regional geological context.

2.5. Geotechnical Study Methodology

In this study, the geotechnical approach involved performing boreholes and in-situ tests to characterize the physical and mechanical properties of the soils at the selected site. This process allows for the evaluation of soil bearing capacity, permeability, and compaction key factors for ensuring the stability and durability of faecal sludge treatment infrastructure. The tests carried out included auger drilling and dynamic penetration tests, in accordance with the recommendations of AFNOR, 1996 and ISO, 2018.

2.6. Adopted Methodology

The adopted methodology was based on:

- Performing light dynamic cone penetrometer (DCP) tests to assess soil compaction and bearing capacity, in accordance with ISO standards (ISO, 2012).
- Excavating manual pits and conducting auger drilling to directly observe geological horizons and collect samples.
- Carrying out laboratory tests including dry density, permeability, and Atterberg limits (liquid limit *WL*, plastic limit *WP*, and plasticity index *IP*), following the recommendations of Das, 2015 and ASTM, 2017.

The results obtained enable the classification of soils according to their suitability for construction and the determination of appropriate foundation conditions. According to Loke, 2000, such investigations are essential to ensure the safety and durability of faecal sludge treatment infrastructure, especially in Sahelian contexts where soils present high variability.

2.6.1. Geophysical Study Methodology

For the geophysical study, the electrical resistivity prospecting method was selected. This technique makes it possible to determine subsurface resistivity distribution and to identify the different geological layers as well as the depth of the water table. It is based on injecting electrical current into the ground via electrodes and measuring the resulting potential difference environments (Loke, 2000 and Samouëlian et *al*., 2005).

In this study, resistivity profiles were acquired using a geoelectrical device equipped with probes and electrodes, and processed with Aidu Prospection and Surfer 13 software. The Wenner–Schlumberger array configuration was used, as it offers a good compromise between vertical and horizontal resolution, making it particularly suitable for Sahelian and desert environments (Mbéguéré et *al*. 2010 and Samouëlian et *al*., 2005).

This method makes it possible to:

- Identify subsurface resistivity distribution to detect the different lithological layers.
- Locate potential aquifer levels and estimate their depth.
- Detect possible discontinuity or weakness zones (faults, fractures).

The instrumentation used included a geoelectrical device, steel probes and electrodes, as well as interpretation software such as Aidu Prospection and Surfer 13. This approach is consistent with practices described by Zongo et *al*., 2010. for similar projects in West Africa.

2.6.2. Hydrogeological Study Methodology

The hydrogeological approach adopted in this study is based on the collection of data on the depth, dynamics, and vulnerability of groundwater aquifers underlying the selected site. This process is essential to prevent the risk of aquifer pollution through effluent infiltration and relies on the analysis of geoelectrical profiles, observation of existing boreholes, and the use of piezometric maps where available (IAEA, 2015). In West Africa, several studies (Semiyaga et al., 2015 and Bassan et al., 2013) emphasize that neglecting these aspects often leads to failures in the sustainable management of faecal sludge.

The hydrogeological study is based on:

- ✓ Analysis of data derived from geoelectrical profiles.
- ✓ Direct observation of existing boreholes and collection of piezometric data.
- ✓ Use of regional hydrogeological maps.

Topographic Study Methodology

The purpose of the topographic study is to:

- ✓ Determine the morphological characteristics of the terrain (slopes, relief, elevations).
- ✓ Provide the basis for technical planning (site layout, sanitation, water management).
- ✓ Deliver accurate mapping (plans, longitudinal and cross profiles) for subsequent phases of the project.

This approach complies with the recommendations of studies of ISO, 2010 on the survey and modelling of topographic data for planning and construction purposes.

- ✓ Fieldwork consisted of:
- ✓ Establishing reference benchmarks: solid marking (masoned iron bars), a standard method to ensure the durability of sighting points.
- ✓ Polygonal surveying: rigorous selection of point locations to ensure measurement stability and continuity.
- ✓ Detailed altimetric and planimetric surveying using a TS10 total station, a high-precision tool with a very low margin of error (< 2 mm over 1 km horizontally).

Data processing involved:

- ✓ Transfer via GEOOFFICE: software dedicated to managing raw total station data.

- ✓ Processing with AutoCAD + Covadis: enabling the production of topographic maps and longitudinal and cross profiles.
- ✓ X, Y, Z representation of the natural terrain, essential for site modelling.

A similar methodology was applied during the urbanization study of Kampala (Uganda), where topographic surveys were used to simulate stormwater runoff and design retention basins (Mugume et *al*., 2015).

2.6.3. Multicriteria Analysis Methodology

In the context of this study, multicriteria analysis was used as an evaluation method to compare and prioritize the different study areas based on several relevant criteria. This approach relies on the simultaneous consideration of geotechnical, geophysical, and hydrogeological factors, each assigned a specific weight according to its relative importance to the issue being addressed. The method involves assigning scores to different alternatives or spatial units based on the selected criteria, which are then aggregated using a predefined weighting system. The goal is to obtain a comprehensive assessment that best reflects the reality of the field and enables rational and justified decision-making. This technique is particularly recommended for environmental and land-use planning studies, as it allows for the integration of divers types of data and reduces subjectivity in the selection of priority intervention areas. Thus, each potential site is evaluated according to a set of predefined criteria. Minimum conditions are defined for each criterion, and a satisfaction level is assigned based on field observations. All criteria are weighted equally, reflecting a choice of fairness among the requirements. This method is akin to the Multi-Criteria Decision Analysis (MCDA) approach, widely used in land-use planning. **Table1** below presents the evaluation method for the site characterization criteria.

Table 1. Evaluation of site characterization criteria

Criteria	Minimum Conditions	Observed State	Remarks	Value Class
1. Distance from the center of gravity of desludging activity	10 km	The farthest point is less than 10 km from the FSTP	The city will only have one FSTP, and its spatial extent diameter is less than 10 km	Satisfactory
2. Area	10 ha	≥110 ha	Sufficient and secured space	Satisfactory
3. Land ownership	Guaranteed	No disputes	The land is owned by the Municipality of Agadez	Satisfactory
4. Neighborhood / urbanization risks / safety distance	Within a radius of 200 m	>200 m	The site is large enough to respect environmental safety distances; the prescribed 200 m safety buffer is respected on all sides	Satisfactory
5. Soil type	Gravelly soil	Open terrain	Based on the results of geological data correlated with the very high geo-electrical values of these layers and their continuity (without major fractures or faults), we recommend construction works in the designated zone, covering an area of 8.504 ha (Annex 2)	Satisfactory
6. Groundwater depth	Safe	150–245 m	Geophysical studies indicate a water table depth ranging from a minimum of 150 m to a maximum of 245 m (water table top)	Satisfactory

7. Topography	Risk-free	Steep slope	A steep slope oriented from North to South, favorable for gravity flow, exists (see cross-section profile – Dari site)	Satisfactory
8. Availability of potable water	Possible connection to the network	No constraints	Possibility of connection to the SPEN network within 1 km (city)	Acceptable
9. Availability of electricity	Possible connection to the network	Feasible	Possibility of connection to the NIGELEC network via the existing medium voltage line within 1 km (city)	Acceptable

3. Results and Discussion

3.1. Geological and Topographical Studies

The geological study reveals the nature of the outcropping formations in the study area. The analysis of the map derived from this geological study shows that the study area primarily consists of sandstone formations (7%), alluvial deposits (43.52%), and clayey sand formations (46.09%). **Figure 3** below presents the various geological formations outcropping within the project perimeter.

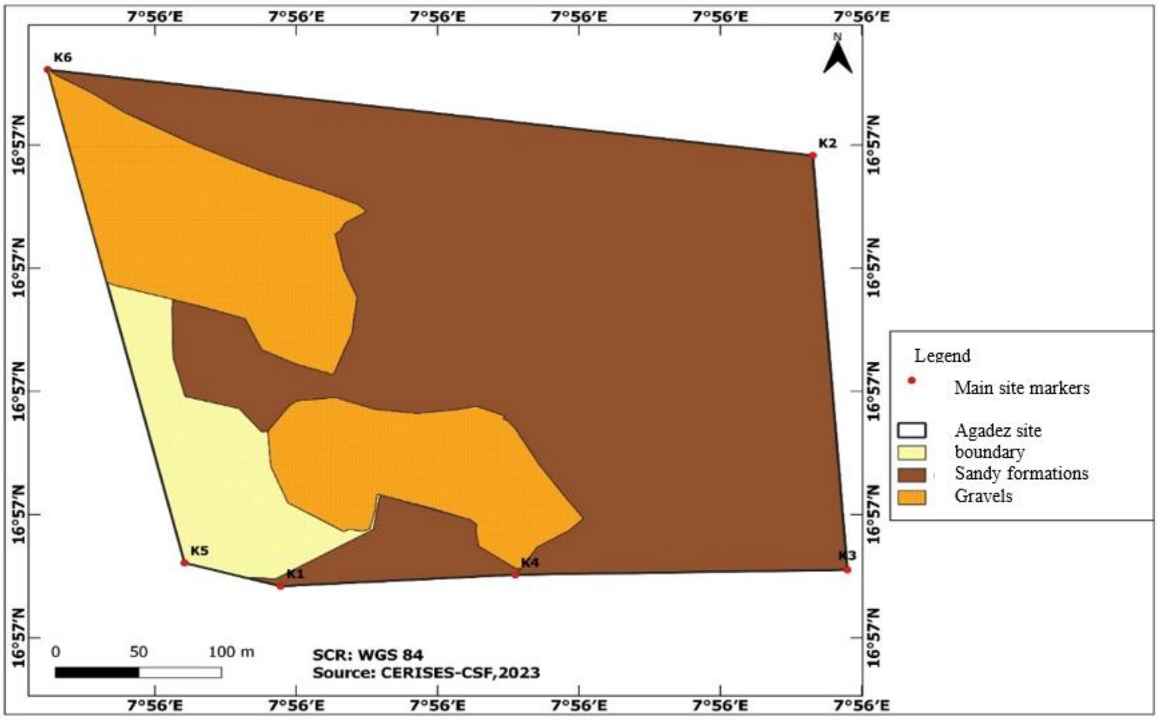

Figure 3. Geological Map of the Study Area

The sandstone formations are compact sedimentary rocks, relatively hard, and generally have good bearing capacity. They can sometimes constitute aquifers if they are fractured. The alluvium (gravel) deposits are loose, highly permeable, favorable for water infiltration, and often host unconfined aquifers. The clayey sands indicate an intermediate soil: the presence of clay can slow down infiltration but also improve water retention. They are less favorable for good bearing capacity for heavy structures if the clay content is high. This indicates a predominance of sandy and alluvial formations, which are favorable for water infiltration. However, the absence of major faults is a positive indicator for the stability of structures. A similar study in the Lake Chad basin showed that clayey-sandy terrains over sandstone substratum had good aquifer recharge potential but required particular attention regarding foundation stability. To gain an understanding of the different land use units in the project area, a map was created. The figure below presents the different land use units within a 10km radius around the study site (**Figure 4**).

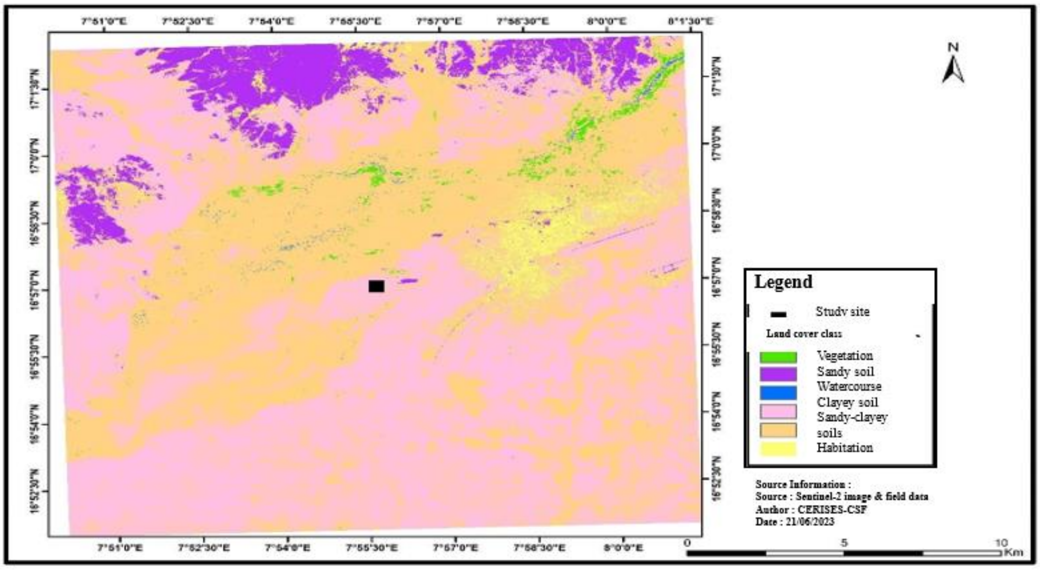

Figure 4. Land Use Map of the Study Area

The analysis of this map reveals that in 2022, the different land use units in the study area are distributed as follows: vegetation covers 0.80% of the total area, sandstone formations occupy 7%, water bodies cover 0.16%, alluvial deposits (gravel) represent 43.52%, clayey sand formations extend over 46.09%, and residential areas occupy 2.43%. This map serves as a valuable tool for monitoring the dynamics of land use units, particularly vegetation, following the completion of construction works. The **Table 2** below presents the distribution of land use units.

Table 2. Distribution of Land Use Units

Unit	Area (%)	Technical and Environmental Interpretation
Clayey sand	46.09 %	Mixed soils with moderate bearing capacity, slow infiltration
Alluvium (gravel)	43.52 %	Excellent permeability, high bearing capacity
Sandstone formations	7.00 %	Good bearing capacity, low permeability
Vegetation	0.80 %	Low vegetation cover, potential erosion
Watercourses	0.16 %	Almost negligible presence
Housing	2.43 %	Low urbanization, limited impact

The analysis of land cover units reveals that the low vegetation cover (0.8%) makes the area particularly vulnerable to wind and water erosion, especially in sandy sectors. The predominance of loose soils, mainly composed of alluvium and clayey sands (approximately 90% of the surface area), indicates a fragility of the soil when exposed to uncontrolled anthropogenic activities such as construction or intensive drilling. Conversely, the absence of large urbanized areas is an asset, as it limits constraints related to land occupation and human-induced pollution.

For the topographic studies, it is important to note that the high level of detail (trees, blocks, watercourses, etc.) and the use of modern equipment (TS10) ensure sufficient accuracy for medium to large-scale technical projects. Digital processing allows for easy reuse of data for simulations (hydraulic, road networks, GIS).

The cross and longitudinal profiles revealed a significant North-South oriented slope (cf. Dari terrain), facilitating gravitational flow, a crucial advantage for sanitation or hydraulic installations. The obtained topographic map provides a georeferenced and usable foundation for all technical phases: earthworks, network layouts, and structure placement. In a construction site evaluation project in rural India, topographic surveys conducted using a total station reduced leveling errors in pipeline projects by 20%.

3.2. Geophysical and Hydrogeological Study

The **Table 3** below presents a synthesis of the geophysical survey work carried out on the Agadez site.

Table 3. Summary of Field Survey Work

Site Name	Line No	Direction	Length (m)	Depth of Conductor Level (Aquifer Zone) in (m)
	L1	N280°	300	190
	L2	N260°	350	140
Agadez	L3	N270°	60	160
	L4	N170°	130	220
	L5	N160°	120	200
	L6	N113°	70	150

The **Figure 5** below shows the location of the geoelectric prospecting lines carried out at the Agadez site.

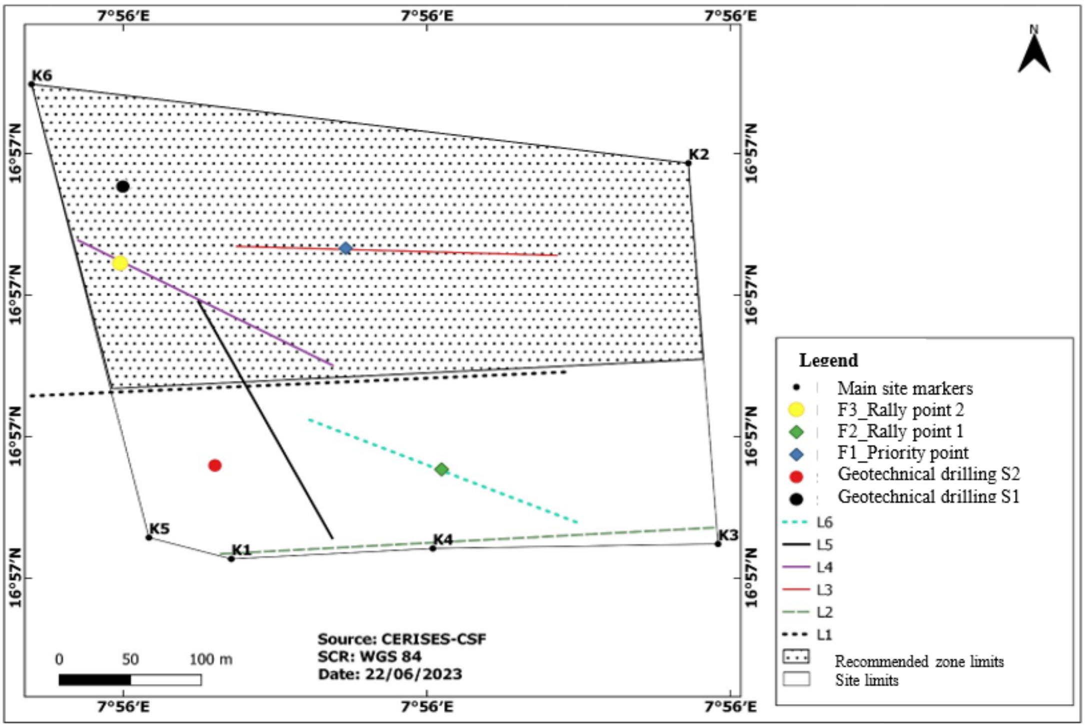

Figure 5. Location of Geoelectrical Survey Lines

The **Table 3** above summarizes the main characteristics of the six geophysical survey lines carried out on the site, indicating their orientation, length, and the estimated depth of conductive layers interpreted as water-saturated aquifer zones. On line L1, a deep aquifer was detected at 190 m. Line L2 reveals an aquifer from 140 m depth, with good vertical continuity. Line L3 highlights an aquifer at 160 m, confirmed by several conductive layers extending down to 250 m. Line L4 indicates a very deep and continuous aquifer zone at approximately 220 m. On line L5, an aquifer was identified at 200 m, showing moderate heterogeneity. Finally, line L6 reveals an aquifer at 150 m, characterized by intercalations of resistant layers. **Figures 6** and **Figure 7** below show the electrical resistivity tomography lines conducted in the study area.

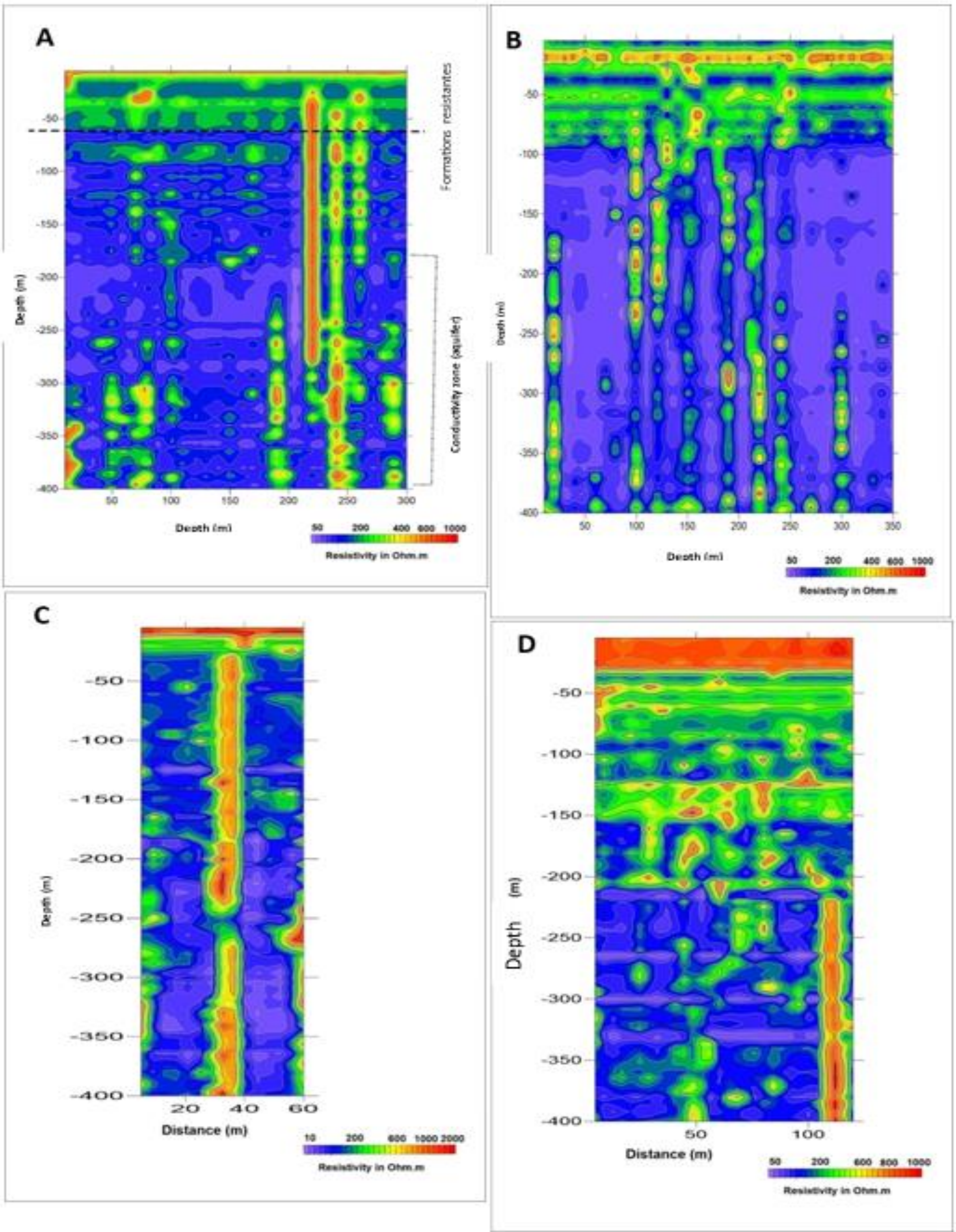

Figure 6. Electrical resistivity tomography line (A: L1, B: L2, C: L3, D: L4)

The interpretation of data from line L1 highlights a stratigraphy characterized by three distinct levels. The first, near-surface layer, resistant between 0 and 65 meters, is likely composed of dry or compact formations. It is followed by an intermediate layer, from 65 to 190 meters, whose higher resistivities indicate very resistant rocks typical of low-permeability environments. At greater depth, between 190 and 400 meters, a conductive layer appears, with resistivities ranging from 50 to 200 Ohm·m, suggesting the presence of a main aquifer. However, the occasional occurrence of resistant zones within this deep level could hinder homogeneous water exploitation by locally reducing abstraction capacity. Line L2 displays a simpler but very clear profile. From 0 to 140 meters, relatively high resistivities (250–600 Ohm·m) reveal a dry, compact medium with limited water circulation. From 140 meters down to about 400 meters depth, values drop (50–200 Ohm·m), indicating a continuous and well-structured aquifer, likely confined beneath an impermeable geological cover. This type of configuration is favorable for protecting the resource from surface contamination.

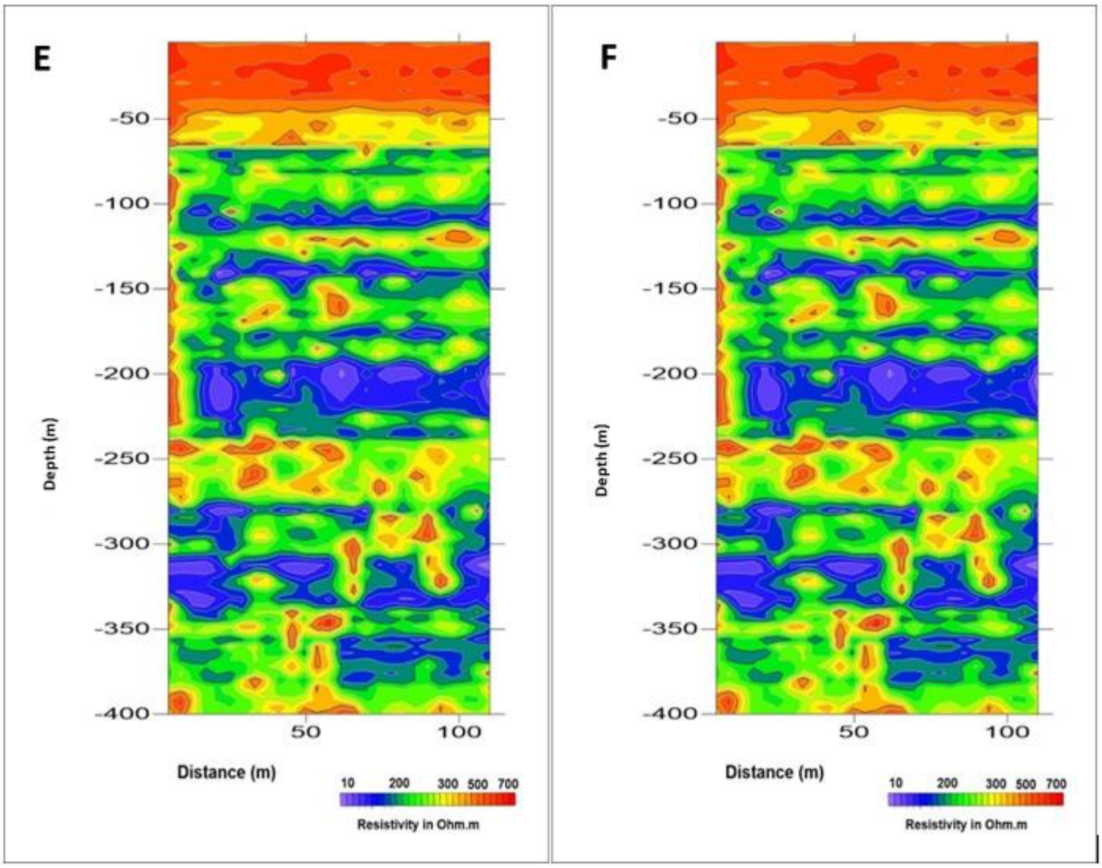

Figure 7: Electrical Resistivity Tomography Line (E: L5, F: L6)

Line L3 shows a more complex geoelectrical behavior. At the surface, down to 150 meters depth, formations are resistant with values ranging from 200 to 1500 Ohm·m, reflecting a dry and compact soil. A short conductive layer is observed between 150 and 160 meters (10–120 Ohm·m), corresponding to a thin but exploitable aquifer. Below 190 meters, resistivities decrease again, suggesting a deeper aquifer. Very resistant zones (up to 2000 Ohm·m) appear as subvertical bands, probably linked to massive rock blocks or structural discontinuities. Analysis of Line L4 reveals a highly resistant structure throughout the upper section down to a depth of 220 meters (250–1000 Ohm.m), indicating a coherent and dry substrate. Beyond this depth, resistivity values ranging between 50 and 190 Ohm.m highlight the presence of a deep aquifer. This profile is distinguished by its high stability and the absence of major anomalies, making it an ideal target for a productive and sustainable borehole. A subvertical anomaly localized between 110 and 120 meters could correspond to a filled fault, with no apparent disruptive effect. Line L5 shows a predominantly resistant environment between 0 and 200 meters (300 –700 Ohm.m), suggesting mostly dry or consolidated soil. However, a significant decrease in resistivity is observed between 200 and 245 meters, signaling a potentially exploitable aquifer level. The remainder of the profile is marked by alternating resistant and conductive zones, revealing a heterogeneous environment, likely due to irregular alluvial deposits or clay lenses interbedded within sandy formations. Finally, Line L6 offers a contrasting interpretation. The surface layer, down to 15 meters, exhibits low resistivity values (100–210 Ohm.m), characteristic of surface clays. From 15 to 200 meters, the profile becomes more resistant

(210 – 640 Ohm.m), but two localized conductive zones at 150 meters and 170 meters indicate the presence of secondary aquifer pockets. Beyond 275 meters, a generalized decrease in resistivity suggests a deeper aquifer, although lateral heterogeneity indicates variability in reservoir thickness and quality (Figure 6 and Figure 7). The implementation of a water borehole on the site is necessary, given its proximity to the NDE supply network (1.5 km). The results of this hydrogeological study reveal that the estimated water table depth ranges between 150 and 245 meters. Three recommended drilling points are identified (250 m, 265 m, and 220 m depth). The proposed site area of 8.504 hectares is considered optimal. The depth of the aquifers, combined with moderate resistivity values, indicates a deep and stable captured water table, with a low risk of contamination from surface discharges. Establishing the borehole in a fracture-free zone ensures sustainable exploitation of the resource. **Table 4** below presents the proposed points for borehole implementation and the predicted drilling depths.

Table 4. Proposed points for borehole implementation and predicted drilling depths

Electrical Tomography Line No.	Priority Order	Type of Structure to be Constructed	Planned Depth (m)	Longitude	Latitude	Altitude (m)
L3	F1_Priorit Point	Productive Borehole	250	7.929465°	16.951330°	525
L6	F2_Backu Point 1	Productive Borehole	265	7.930097°	16.949768°	524
L4	F3_Backu Point 2	Productive Borehole	220	7.927978°	16.951225°	526

3.3. Geotechnical study

The geotechnical investigations focused on:

- Light dynamic penetrometer tests (S1 to S4),
- A manual well to observe the stratigraphy,
- Laboratory analyses: dry density (γd), permeability (K), and Atterberg limits (Wl, Wp, IP),
- Soil classification based on soil properties.

Four (4) soundings and one (1) well were carried out in order to properly assess soil constraints. The coordinates of the borehole locations on the site are shown in the following **Table 5**.

Table 5. Coordinates of borehole locations on the site

N°	Geographical coordinates	
	Latitude values	Longitude values
S1	N 16,949643°	E 7,929020°
S2	N 16,951363°	E 7,928287°
S3	N 16,950752°	E 7,929595°
S4	N 16,949707°	E 7,930366°
PUIT	N 16,9498213°	E 7,931590°

The **Table 6** below shows the results of the geotechnical study determined in the laboratory. The results of the geotechnical tests (**Table 6**) conducted on the site show characteristics favorable to the implementation of foundation works. The light dynamic penetrometer tests reveal refusal at less than 1.00 m depth, indicating a dense surface soil, particularly suitable for shallow structures. This initial good bearing capacity represents a significant advantage for the stability of the infrastructure.

Table 6. Results of the geotechnical study determined in the laboratory

Parameter	Sandstone	Sandy Clay	Average	Interpretation
Dry Density γd (kg/m³)	2.07	2.04	2.065	Good compaction (>2.0 g/cm³)
Permeability K (m/s)	4.81×10^{-7}	4.33×10^{-5}	2.19×10^{-5}	Low permeability (cohesive soils)
Wl (Liquid Limit)	34	29	31.5	Medium to high plasticity
Wp (Plastic Limit)	18.68	17.51	18.09	—
IP (Plasticity Index)	15.32	11.49	13.41	Plastic soils (clayey)

The stratigraphy observed from the manual borehole highlights two distinct layers: a first layer of sandy clay from 0 to 0.20 m depth, characterized by low bearing capacity and high plasticity, followed by a layer of clayey sandstone between 0.20 and 0.80 m, offering more stable mechanical behavior and better cohesion. This bistratified structure is typical of transitional environments between fluvial deposits and consolidated continental formations (Briaud, 2013).

In terms of mechanical properties, the average dry density measured is 2.065 g/cm³, with values of 2.07 g/cm³ for the sandstone and 2.04 g/cm³ for the sandy clay. These results indicate good compactness of the in-situ materials, enabling them to support moderate to high loads, typical of public or industrial foundation works. At the same time, the average soil permeability is estimated at 2.19×10^{-5} m/s, reflecting low to moderate permeability, typical of cohesive soils such as clays and clayey sandstones. This low permeability significantly reduces the risks of excessive infiltration and internal erosion, although it requires rigorous drainage management in case of heavy rainfall.

Atterberg limits complete the mechanical analysis of the soil: the average liquid limit (Wl) is 31.5%, the plastic limit (Wp) is 18.09%, and the plasticity index (PI) is 13.41%. These values place the soil in the category of moderately to highly plastic soils, which implies viscoplastic behavior sensitive to water content. In this context, it is essential to provide for accurate foundation design in order to avoid differential settlement or unpredictable soil behavior during periods of saturation.

Overall, the sandstones observed on the site have satisfactory mechanical stability, particularly in semi-arid Sahelian areas (Yong et *al*., 2012). Their compactness and low permeability make them geotechnically reliable materials. Thanks to its geomechanical profile, the soil studied is suitable for the construction of heavy structures, provided that precautions are taken in the choice of foundation system and seasonal variations in soil moisture are taken into account. **Figure 8** below shows the stratigraphic log of the study area.

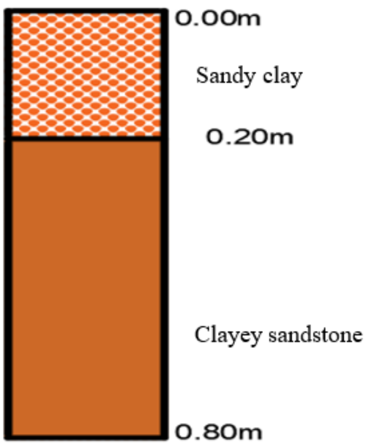

Figure 8. Stratigraphic log of the study area. Multi-criteria analysis

Table 7 below presents the results of the multi-criteria analysis based on the nine site evaluation criteria, along with their satisfaction status. Analysis of Table 7 shows that the site meets all essential criteria. The site's proximity to the center of gravity of the waste disposal activity, estimated at less than 10 kilometers, is a significant logistical advantage. This location significantly reduces transportation costs and times, thereby optimizing operational efficiency and limiting the environmental impact of travel. The available area, which exceeds 110 hectares, far exceeds the minimum requirement of 10 hectares. This size ensures flexibility in terms of development, not only for the immediate needs of the project, but also for possible future extensions. In terms of land ownership, the site is public property and is not subject to any disputes, which eliminates any risk of legal conflict and facilitates the obtaining of the necessary authorizations. In addition, the safety distance from residential areas, which is more than 200 meters, is respected. This compliance with standards reduces potential nuisances (noise, odors, traffic) and minimizes the risk of conflicts of use with local residents.

Table 7. Results of the multi-criteria analysis based on the nine site evaluation criteria, along with their satisfaction status

Criterion	**Observed Condition**	**Rating**	**Comments**
1. Distance from the center of sludge disposal activity	< 10 km	Satisfactory	Proximity favorable for reducing transportation costs.
2. Area	≥110 ha	Satisfactory	Well above the required threshold (10 ha), ensuring ample room for development.
3. Ownership	Public domain without dispute	Satisfactory	Avoids land conflicts and facilitates site development.
4. Surroundings / Risk of urbanization	Safety radius respected (>200 m)	Satisfactory	Reduces nuisances and risks of land-use conflicts.
5. Soil type	Stable gravelly	Satisfactory	Suitable for the construction of heavy structures. Confirmed by geophysical survey.
6. Groundwater depth	150–245 m	Satisfactory	Depth ensuring good protection against contamination.
7. Topography	Natural slope	Satisfactory	Promotes gravity drainage, reducing operational costs.
8. Drinking water availability	Network at 1 km	Acceptable	Possible connection, although not immediate.
9. Electricity availability	Network at 1 km	Acceptable	Connection possible via medium-voltage line.

From a geotechnical point of view, the soil is stable gravel, favorable for the construction of heavy structures. Geophysical investigations confirm this stability, thus limiting the risk of differential settlement or landslides. The water table is located between 150 and 245 meters deep, providing good protection against pollution and ensuring a sustainable water supply. In addition, the natural topography of the site, characterized by a gentle slope, facilitates gravity flow, which reduces energy consumption related to pumping and, consequently, operating costs. Only two criteria are classified as acceptable: the presence of drinking water and electricity. In both cases, the networks are located approximately one kilometer from the site, which requires connection work but does not represent a major technical or financial obstacle. The site is almost perfectly suited to the technical, functional, and regulatory requirements of the project. Its main advantages are its high land availability, confirmed geotechnical stability, clear legal status, proximity to business parks, and favorable topography. The improvements needed to ensure water and electricity supply are simple to implement and do not affect the overall viability of the project.

Conclusion

The hydrogeological, geotechnical, geophysical, and topographical studies conducted at the proposed site in Agadez have established, in an integrated and precise manner, its suitability for the construction of a sewage sludge treatment plant. The investigations revealed good soil bearing capacity, a deep-water table (150 to 245 m) well protected against pollution risks, a topography favorable to gravity flow, and no major land constraints. The multi-criteria analysis confirms that the site meets almost all technical, environmental, and regulatory requirements, thus ensuring the sustainability and future efficiency of the infrastructure. The establishment of this plant is an essential step towards sustainably improving sewage sludge management in the Agadez region, reducing health and environmental risks, and contributing to national and international sanitation and public health objectives.

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