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Original Research

Use of ground penetrating radar (GPR) for coastal aquifer characterization in Garopaba/SC

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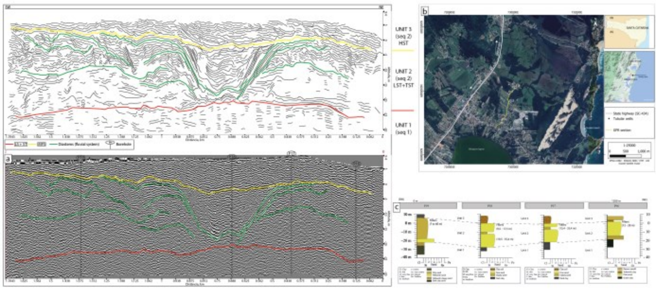

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Abstract: The work analyzes the sedimentary deposits of the coastal aquifer of the locality of Limpa, Garopaba (SC), through geophysics and well data. A ground penetrating radar section (GPR) was acquired in an area adjacent to 4 wells located in the south of the municipality, provided by the water and sanitation company (CASAN). Three lithostratigraphic units were identified, with a basal layer composed of clayey material, an intermediate layer predominantly composed of sand representing the aquifer unit, and a superficial layer composed of fine sediments, peat and sand. The GPR section presents a paleochannel feature within the aquifer unit, showing the lateral variation of facies and depositional architecture within a lithological unit. The interpretation of key surfaces, textures and reflector termination patterns led to the diagnosis that the intercepted sedimentary deposits represent two depositional sequences, probably of Pleistocene age, composed by the record of lagoon-barrier and fluvio-estuarine systems. The lateral and vertical variation of sedimentary deposits has a significant influence on the hydrodynamic behavior of aquifers, so that the detailed scale characterization of the coastal aquifer can help the management of water resources, especially in areas extremely vulnerable to contamination and with high water demands, as is the case of Garopaba.

Keywords: Georadar, hydrogeology, environmental stratigraphy, water resources.

Introduction

The coastal plain of Santa Catarina is a dynamic and constantly-changing environment influenced by natural and anthropogenic processes. Although the region has been inhabited for at least 7,000 years [1], land use and occupation have intensified in recent decades, leading to concerns and conflicts regarding natural resources, especially groundwater. Recent human settlement has mainly developed over Pleistocene and Holocene sedimentary deposits, products of coastal dynamics and sea level variations during the Quaternary.

Garopaba is located 90 km south of Florianópolis, with an area of 114.670 km² and an estimated population of 24,070 people by IBGE in 2021. The region lies within the boundary of the Pelotas and Santos Basins, forming the Coastal Province of Santa Catarina. It is composed of hills, promontories, and rocky outcrops of the pre-Cenozoic crystalline basement [2], and in the plain areas, there are sedimentary covers, mainly Pleistocene and Holocene lagoon-barrier deposits, as well as Cenozoic colluvial and alluvial deposits, fluvio-lacustrine deposits, and anthropogenic deposits [3, 4].

Regional and local mapping identifies the Garopaba coastal aquifer as an area of extreme natural vulnerability, where sewage, lack of environmental sanitation, industrial effluents, saline intrusion, and agricultural activities (nitrates and pesticides) pose high risks of contamination [5–7]. The Water Resources Plan of the Cubatão, Madre, and Adjacent Basins [8] points out that the Siriú Management Unit, which includes the study area, is critical from a quantitative point of view (water availability) for the expansion of groundwater-demanding activities. This situation is exacerbated during the summer season, as the municipality mainly relies on groundwater for its water supply.

The significant growth of the municipality implies an increase in environmental impacts and the exploitation of water resources. In this context, the present study aimed to analyze the geology of the groundwater capture areas in Garopaba through the analysis of tubular well data and subsurface analysis with ground penetrating radar (GPR). The objective is to understand the paleoenvironmental evolution of the system and its influence on hydrostratigraphy, contributing to better water resource management. The study area is located in the Limpa neighborhood in Garopaba/SC, between SC-434 highway and Ouvidor beach (Figure 1).

Experimental Section

In this section, we outline the methodology employed to investigate the hydrogeological and stratigraphic features of the study area. Our approach encompasses a combination of GPR profiling and well data analysis, in addition to geoprocessing methods.

Borehole Sections

The hydrogeological characterization was based on the analysis of the construction profile of four operational tubular wells located on Limpa General Road and Campos da Limpa Street (Fig. 1), provided by the water and sanitation company (CASAN). The data used included lithology, final depth, filter depth, static water level, and flow rate. The database was organized in an Excel spreadsheet, and graphical illustrations of the borehole profiles were created using Adobe Illustrator CC2019.

Ground-Penetrating Radar (RGP)

The GPR survey produced a profile with a length of 1,703 m and a depth window of 30 m, conducted along the road adjacent to the tubular wells. Data acquisition was performed using a GPR device with a collector acquisition system, the Cobra Plug-In GPR (Radar team Sweden AB), equipped with a SUBECHO SE-70 airborne antenna with a central frequency of 80 MHz, connected to a GNSS receiver (TRIMBLE® Pro-XRT), allowing real-time topographic data acquisition.

Data processing was carried out in the laboratory of the Center for Coastal and Ocean Geology Studies (CECO) of the Institute of Geosciences IGEO/UFRGS. The data processing steps followed the procedures suggested by [9] and [10], including zero-time correction, signal saturation correction by removing low frequencies, application of gains (amplification of attenuated signals), application of vertical bandpass filters, application of horizontal spatial filters to remove environmental and systematic noise, conversion of time depth into distance, removal of surface-derived reflectors, and topographic correction.

The interpretation of the data is based on the principles of seismic stratigraphy applied to GPR [9]. It involves identifying patterns of internal reflector geometries and terminations (onlap, downlap, toplap). The identified patterns are then related to the stratigraphic units comprising the coastal

Figure 1. Location of the georadar section and analyzed groundwater wells in the south zone of Garopaba, in the area with Imbituba city. Lagoon systems can be seen to the north and south, as well as the extensive Ouvidor dune field to the east.

Sci. cum Ind. **2025**, 14(2), e251425. DOI: 10.18226/23185279.e251425

Quaternary depositional systems. Limit surfaces between system tracts and sequence boundaries are identified following [11].

Geoprocessing

The tubular wells and the GPR section were georeferenced on a hypsometric map using the QGIS 3.16.7-Hannover program. The data utilized the digital terrain model of the State of Santa Catarina from 2016, with a spatial resolution of 1 m and an altimetric accuracy of 1 m. Correlations with geological and hydrogeological data were based on the works of [3–6].

Results

In this section, we first present the results of the geological characterization led by a comprehensive examination of well data. Next, we delved into the analysis of a prominent fluvial channel feature observed in the GPR data, exploring its genetic origins. The hydrogeological variations are discussed in the context of local topography and its potential influence on aquifer thickness. We conclude by emphasizing the significance of standardized drilling data and their pivotal role in understanding aquifer complexities, thereby enhancing our ability to predict and manage these vital groundwater resources.

Borehole Sections

The four wells are oriented SW-NE, from P19 to P16, respectively, with a distance of 1,200 m between the first and the last well and an average depth of 39 m (Figure 2). Field descriptions were interpreted, standardized, and classified into 3 sedimentary units or hydrostratigraphic layers with distinct characteristics that allowed lateral correlation. These units are: 1) a basal layer with clay presence, 2) an intermediate layer with fine to medium-grained sandy packages, and 3) a superficial layer of fines with organic matter.

All wells have a basal layer (Unit 1) with clay/silty sand occurrences, with color variations of black, gray, and green. This unit has an average thickness of 8 m down to the well's base. The top of the layer occurs at an average depth of 31 m. Above the basal layer, there are sandy packages (Unit 2) that form the local aquifer system. The sandy layer, the thickest hydrostratigraphic unit, at 18 m, occurs in well P19. Lenses of silty sand, up to 2 m thick, are found in this unit between wells P18 and P17. Except for one well (P16), all have a superficial clayey soil layer with a thickness of 4 to 8 m (Unit 3). P16 is distinctive because it has a superficial layer of yellowish sandy soil with a thickness of 4 m. Beneath the superficial layer, a 2 m layer of yellowish clay 'seals' the top of the aquifer unit, which occurs between 6 and 22 m deep.

Regarding water production, the theoretical flow rate of the wells increases from P16 to P19 (Q-P16: 21 m^3/h; Q-P17: 23.3 m^3/h; Q-P18: 33 m^3/h; and Q-P19: 58 m^3/h). The thickness of the filter layers follows the same pattern (P16: 16 m; P17: 20 m; P18: 24 m; and P19: 40 m). One of the explanations for P19's productivity is related to the greater saturated thickness of the aquifer, therefore there is greater reserve and exploitation capacity through the well. The upper depth of the filter layer for P19 is not provided in the construction profile report. Water extraction occurs in the free granular aquifer corresponding to the Coastal Cenozoic and Marine Systems [5]. This aquifer is characterized by good water quality for all purposes and provides good flow rates (between 20 and 90 m^3/h), although it exhibits extreme natural vulnerability with a high risk of contamination from sewage due to the lack of environmental sanitation and pesticides and nitrates in agricultural areas.

Ground-Penetrating Radar

The interpretation of the GPR section allowed the identification of three main sets related to depositional systems (Figure 3). From bottom to top, the successive depositional systems are marine/estuarine, fluvio-estuarine, and shoreline (coastal barrier or lagoon margin).

The basal unit (1) consists of concordant sub-horizontal and sinuous reflectors, gently dipping to the NE between wells P17 and P16 and dipping to the SW to the south of P19. The reflectors exhibit lateral continuity, although the signal is affected by attenuation and hyperbolic interference. Following the sequence stratigraphy principles [11], sequence boundary surfaces (LS) and transgressive surfaces (ST) were interpreted at the top of Unit 1. It is observed that in a shallow platform environment, lowstand system tracts are rarely recorded, which is why the transgressive surface (ST) is indicated in conjunction with the sequence boundary surface (LS) between Units 1 and 2.

The intermediate unit (2) exhibits at its base a significant erosional feature and channel infilling, with the channel being intercepted by well P18 at an approximate depth of 20 m. The base of the channel wa interpreted as the sequence boundary surface (LS) and the transition from a high stand system tract (from the previous sequence) to a low stand and transgressive system tract. Over the channel, the reflectors dip from the margins to the bed, terminating in downlap within the depocenter. Along the channel infilling, onlap terminations are identified. The maximum flooding surface (MFS) indicates the top of Unit 2 and the boundary between the transgressive and high stand tracts.

The superficial unit (3) is marked by strong reflector signals dipping to the NE, with downlap terminations on the MFS. The dipping direction contrasts with the regional Holocene aeolian pattern (dunes migrate to the SW, under NE winds). The reflector behavior can be understood as the result of lagoon margin progradation or an ancient coastal barrier.

The electric energy produced was dissipated on the electric resistances immersed in running water. The frequency, voltage, current, and power of the electric generator were monitored by an energy analyzer (Embrasul RE6000). The engine speed was verified by means of a tachometer and the engine exhaust temperature was verified by means of a K-type thermocouple. The thermocouple was installed in contact with the combustion

Sci. cum Ind. **2025**, 14(2), e251425. DOI: 10.18226/23185279.e251425

gases in the engine exhaust manifold at a point closest to the outlet of the combustion chamber. Exhaust emissions were investigated using a MRU Instruments Optima7 gas analyzer. This device allows the acquisition of the emissions levels of gases such as O_2, CO_2, CO, NO, NO_2, NO_X, and SO_2, as well as the relative air-fuel ratio.

Fuel consumption was measured using a load cell. The data was recorded using an HBM QuantumX MX440B data

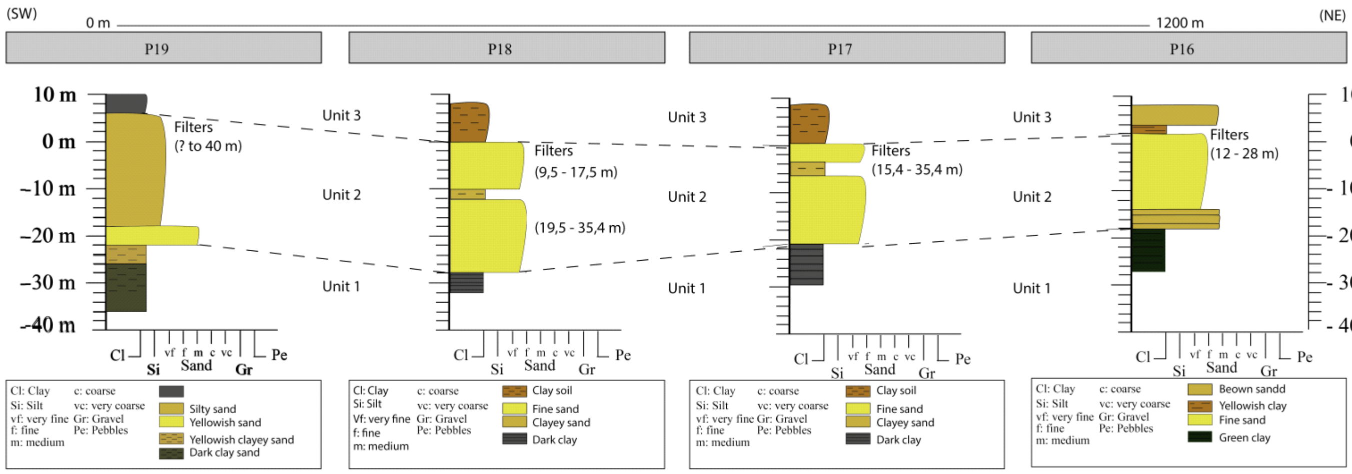

Figure 2. Stratigraphic profile of wells showing the characterization of hydrogeological units. The intermediate sandy layer corresponds to the aquifer hydrostratigraphic unit. A homogeneous clayey layer is observed at the base of the sections, and a heterogeneous layer of fines partially sealing the entire aquifer unit.

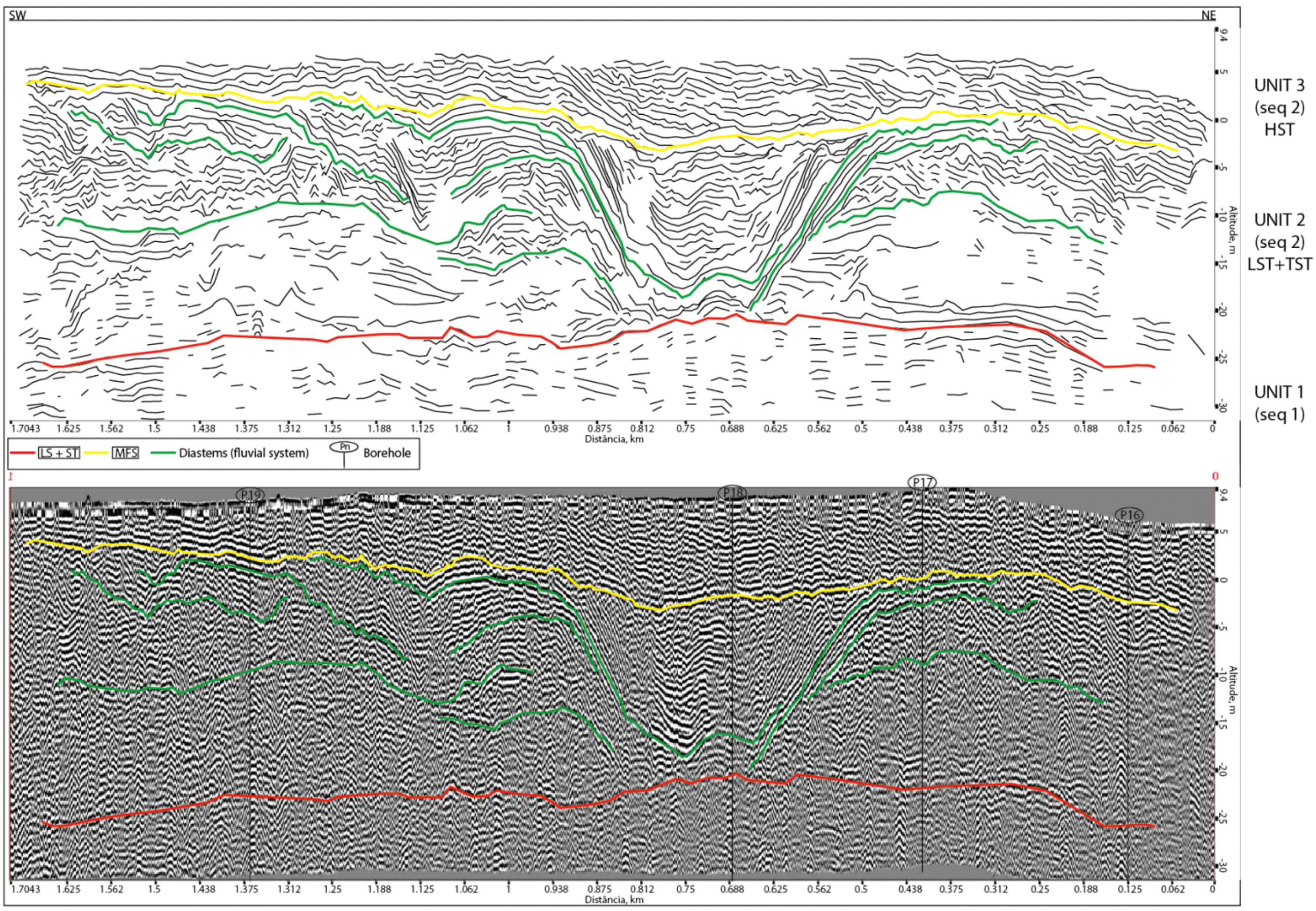

Figure 3. Georadar section (processed below and interpreted above) with identification of the channel structure in the aquifer layer and location of the wells.

Sci. cum Ind. **2025**, 14(2), e251425. DOI: 10.18226/23185279.e251425

acquisition board with Catman software. The change in mass over a certain period of time and the fuel mass flow rate. Information about the instruments and uncertainties are shown in Table 3.

Geoprocessing

The analysis of the digital terrain model in conjunction with geological maps, such as [3], shows that the study area is situated on sedimentary deposits mapped as belonging to a Pleistocene barrier (Figure 4). It was found that there is a topographical correlation between the mapped units. The unit to the north, identified by [3] as ancient undifferentiated Quaternary coastal ridges, is at lower altitudes (< 3 m) than the Pleistocene unit, which ranges between 3 and 10 m (higher altitudes near the basement elevations).

The wells are located on the watershed between the Encantada micro-basin to the north, corresponding to the Madre Basin, and the Ibiraquera Lagoon to the south, corresponding to the D'Una River Basin. Considering that groundwater flow should roughly correspond to topography, the location of wells P19 and P18 tends to favor the water intake due to their central and relatively elevated areas, which results in a greater sediment thickness and infiltration catchment area. On the other hand, wells P17 and P16 are closer to the drainage network flowing into Encantada Lagoon, favoring discharge in the water balance.

Discussion

Regarding the geological characterization, it's important to note that due to the lack of standardization in field descriptions (conducted by third-party companies during well drilling), the interpretation and correlation of the wells were only possible through some generalizations and subjectivity. There is no database with samples or a more detailed sedimentological classification (e.g., Shepard diagram). It is known that different lithofacies within the same depositional system have distinct hydrodynamic properties [12]. Therefore, systematization in mapping the units that make up the aquifer systems is essential for sustainable water resource management.

The identification of an erosive surface interpreted as the paleochannel of a fluvial system in the GPR section led to the analysis of three hypotheses: the drop in sea level due to high-frequency glacioeustatic oscillations (as responsible for the genesis of lagoon-barrier systems and related depositional sequences interpreted by [13, 14], a higher-frequency sea-level

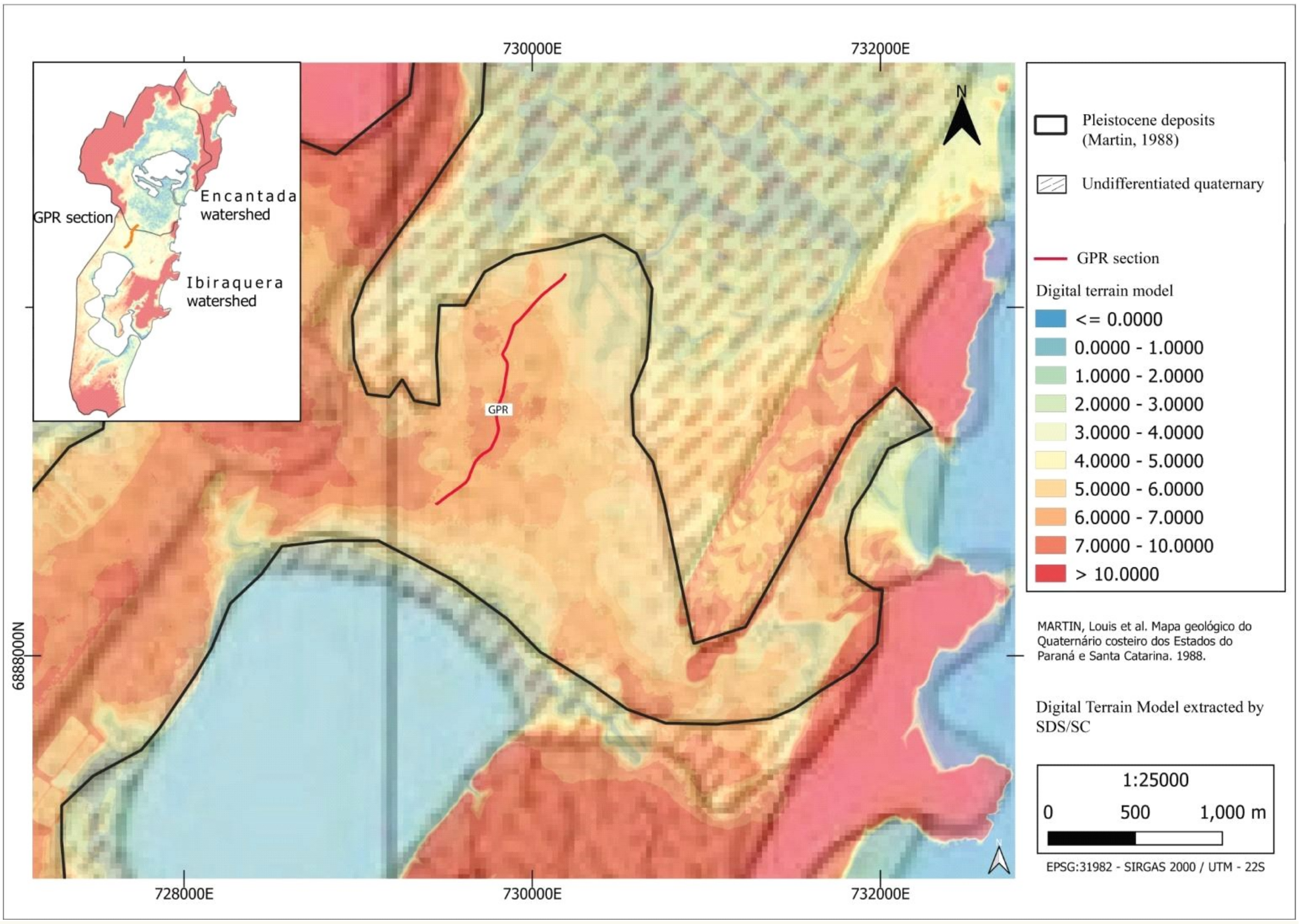

Figure 4. Spatial analysis from geological and topographic data, showing that the GPR section is located at a pleistocenic terrain.

Sci. cum Ind. **2025**, 14(2), e251425. DOI: 10.18226/23185279.e251425

oscillation [14–16], or as an autogenic product resulting from fluvial dynamics [17–19].

The integrated analysis of well data, GPR section, digital terrain model, and geological maps, considering the elevations and positions of Holocene coastal systems, indicates that the studied area corresponds to Pleistocene-age deposits. This analysis led to the consideration of the presence of parts of two Pleistocene depositional sequences, starting from the premise that the erosive surface of the channel represents a sequence boundary [11]. In terms of genesis, it is initially interpreted that this sequence boundary is related to the drop in relative sea level correlatable with isotope stage 6 of $\delta18O$. The drowning of low-lying areas and the filling of the channel occurred during the penultimate interglacial period (isotope stage 5 of $\delta18O$), with the maximum rise in relative sea level estimated at around 120 ka [20, 21]. Thus, the basal sequence would be related with Sequence or System II defined for the coastal plain of Rio Grande do Sul, and the upper sequence with Sequence or System III [14]. The lithostratigraphic units related to the transgressive tracts were generated in a fluvio-estuarine context, while the high-level units represent the record of a coastal barrier or a lagoon margin. The preservation of the record may be conditioned by the influence of rocky promontories on coastal dynamics, promoting sediment accumulation and attenuating erosional processes resulting from the last rise in relative sea level. Hydrographically, the study area is located at the watershed divide between the Ibiraquera basin (to the south) and the Encantada basin (to the north). The presence of the channel in this position was conditioned by a distinct paleogeography, the evolutionary details of which can help understand hydrogeological heterogeneities and the current hydrographic configuration.

The fluvial channel identified in the section is an example of how a hydrostratigraphic unit can exhibit heterogeneities on a local scale, although unconfined granular aquifers are usually understood to be continuous, homogeneous, and isotropic on a regional scale. However, fluvial systems can exhibit a range of facies and hydrodynamic properties. While there may be similarities in terms of sedimentology and a grouping in the simplification of drilling descriptions, the correlation of the wells with the GPR section shows that the aquifer unit does not correspond to a single geological unit. It exhibits variations in architecture, systems, and interpreted depositional sequences. In terms of water production, the theoretical flow of the wells increases from P16 to P19 (Q-P16: 21 m^3/h; Q-P17: 23.3 m^3/h; Q-P18: 33 m^3/h; and Q-P19: 58 m^3/h), with P19 having the thickest deposits correlatable with System II. Although the description indicates a large thickness of silty sand, which could be a simplification of the description, the well is located on a more pronounced relief, raising the question of whether productivity is conditioned by variations in the elevation of the direct capture area. It is important to highlight that wells P19 and P18 have thicker filtering sections, which can help to understand the higher production capacity in these wells. Another hypothesis considers that the superficial layer of peat in P19 may retain more water than the adjacent soil layers, thus feeding the aquifer system of this well.

Conclusions

From the analysis of well profiles and a GPR section, three hydrogeological units were identified, which can be correlated with the evolution of two depositional sequences generated in response to sea-level variations, likely during the Pleistocene. The aquifer unit exhibits variations in depositional architecture identified in the GPR section, which can be related to variations in well production, contradicting the common perception of continuity, isotropy, and homogeneity as hydrogeological conditions of unconfined granular aquifers. Topography may indicate a thicker hydrostratigraphic unit; however, the proximity to the bedrock should be considered. Therefore, a detailed mapping with a GPR grid, sampling, and characterization of lithological units should assist in the hydrogeological characterization of the coastal aquifer. Furthermore, the importance of standardizing well descriptions and data collection during drilling, which form the basis for understanding the stratigraphic control of aquifer system heterogeneities, is emphasized. This understanding has a significant impact on predictive capacity and, consequently, aquifer system management.

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Authors Contribution

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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