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Assessing the Origin and Mapping the Extension of Salinity Around Shrimp Culture Ponds in Rio Grande Do Norte (Brazil)

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Abstract: The increasing installation of shrimp farms in vulnerable coastal areas around the world generates an environmental impact and makes it urgent to develop methodologies and studies for assessing and scaling the potential risks and sustainability of these activities. One of the main hazards of these activities is that the prolonged inundation of excavated ponds for shrimp farming allows the percolation of saltwater in the surroundings, resulting in increasing groundwater salinity. Saltwater intrusion in coastal aquifers, accompanied by salinization of soils, causes a decrease in available freshwater resources, a decline in crop productivity and the deterioration of the natural ecosystem. The coastal aquifer of Rio Grande do Norte State (Brazil) where, for years, several shrimp farm factories have been operating, reported some issues related to aquifer and soil salinization. The present study aims to assess the origin of and delineate groundwater salinization in a sector of this coastal aquifer using a low-budget procedure. The integration of hydrogeological and hydrogeochemical characterization by drilling shallow piezometers, measuring the hydrostatic level and analyzing the major ion concentrations of the groundwater has made it possible to establish that the origin of groundwater pollution in the studied area is caused by saltwater percolation from shrimp farms. The joint use of both characterization techniques has been shown to have an efficient cost–benefit ratio and less-intrusive methodology, which can be applied in other areas with similar environmental concerns.

Keywords: aquaculture; coastal aquifer; groundwater salinization; hydrochemical analysis

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1. Introduction

Increasing water salinity in coastal areas is a significant worldwide concern. Among the different activities threatening the natural environment, shrimp farming stands out as one of the most menacing anthropogenic changes for the ecological sustainability of sensitive coastal areas [1]. Shrimp can be farmed in a wide range of salinities, from freshwater to hypersaline waters [2,3]. Freshwater cultivation leads to a decrease in drinking water reserves [4] and, at the same time, data are accumulating that shrimp cultivation in saline waters also indirectly negatively affects freshwater resources [5,6]. In coastal areas, operation practises mostly consist of taking water directly from the sea by pumping through excavated channels on land near the sea and then discharging into ponds where the prawn farming takes place. As ponds normally do not have adequate waterproofing, stored water and effluents generated during shrimp farming percolate in the subsurface and reach groundwater. Consequently, despite the positive economic outcomes achieved by the entrepreneurs, shrimp farming activity still is frequently associated with severe negative social and environmental impacts such as affecting mangroves and wetlands ecosystems as well as water salinization due to seawater intrusion or poorly-developed pond drainage systems [7–11].

Shrimp farming has undergone extraordinary expansion in the last 25 years, from less than 9000 million tons (MT) to more than 1 million MT (with a first sale value of US$ 6 billion), which is equivalent to about one-third of the total world shrimp supply. About 80% of farmed shrimp is produced in Asia (in particular, in Thailand, followed by China and Indonesia), but the other 20% is produced mainly in Latin America, where Brazil, Ecuador, and Mexico are the largest producers. However, although the prawn aquaculture sector has demonstrated production and financial success, its rapid growth has resulted in several technical, environmental, economic, and social issues [12]. In many locations, the land will be incapable of supporting any agricultural or natural activity when prawn production ends, which frequently happens in a matter of years. The problem of abandoned shrimp ponds is becoming increasingly relevant. For example, it is estimated that in 1994, the top four producing countries abandoned 15,000 hectares of ponds [13], there were 250,000 ha of abandoned ponds in Indonesia [14], and 90% of Sri Lanka ponds [15] and 70% of Thailand ponds [16] have been abandoned recently after a few years of operation [17].

Due to its vast coastline acreage, year-round warm sea temperatures, robust agro-industrial foundation, and appealing domestic market, Brazil has long been acknowledged as having the perfect environment for the growth of prawn farming [18,19]. In 2021, Brazilian shrimp production reached 120,000 MT, mainly concentrated in the coastal areas of the northeast, where the area committed to shrimp farming is approximately 18,500 ha [20].

The first experiments with shrimp cultivated in Brazil date back to the 1970s when the Government of Rio Grande do Norte created the Shrimp Project to study the viability of the cultivation of this crustacean in place of salt extraction, a traditional activity of the State. Salt extraction at the time faced serious price and market crises with consequent widespread unemployment in the salting areas. At the same time, the Brazilian Institute of Colonization and Agrarian Reform (INCRA) has been developing a policy of land reform throughout the national territory intending to ensure social rescue to new settlers. However, often, their opportunities are threatened, as is the case of the serious salinization process in the settlement of Baixa Quixaba (State of Rio Grande do Norte, Brazil). There has been accelerated environmental degradation (including the death of native trees and natural flora), groundwater salinization, and decreased fertility of the soils for the livelihood of the settled families after several ponds for shrimp cultivation were installed.

The assessment of the extent of salinization and pollution of soils and groundwater by seepage, discharge, and flooding associated with shrimp farming requires a clear understanding of the morphodynamic behaviour of these complex environments with extensive, methodical, careful, and expensive surveillance (e.g., [21,22]). The development of cost-effective methodologies that help to establish environmental and sustainable policies in such environmentally sensitive coastal areas could be a suitable objective. For this purpose, the main goal of this research is to evaluate the usefulness of the joint use of widespread hydrogeological and hydrochemical methods to delineate the area affected by the impact of groundwater salinization and unveil the origin of salinization. The hypothesis was to determine whether salinization is the result of a natural process of marine intrusion or the effect of infiltration and recycling of hypersaline waters because of shrimp farming practises carried out in onshore ponds.

2. Geographical and Climate Setting

This study area is on the north coast of Rio Grande do Norte State (Brazil), next to a settlement administered by the INCRA called Baixa da Quixaba (Figure 1).

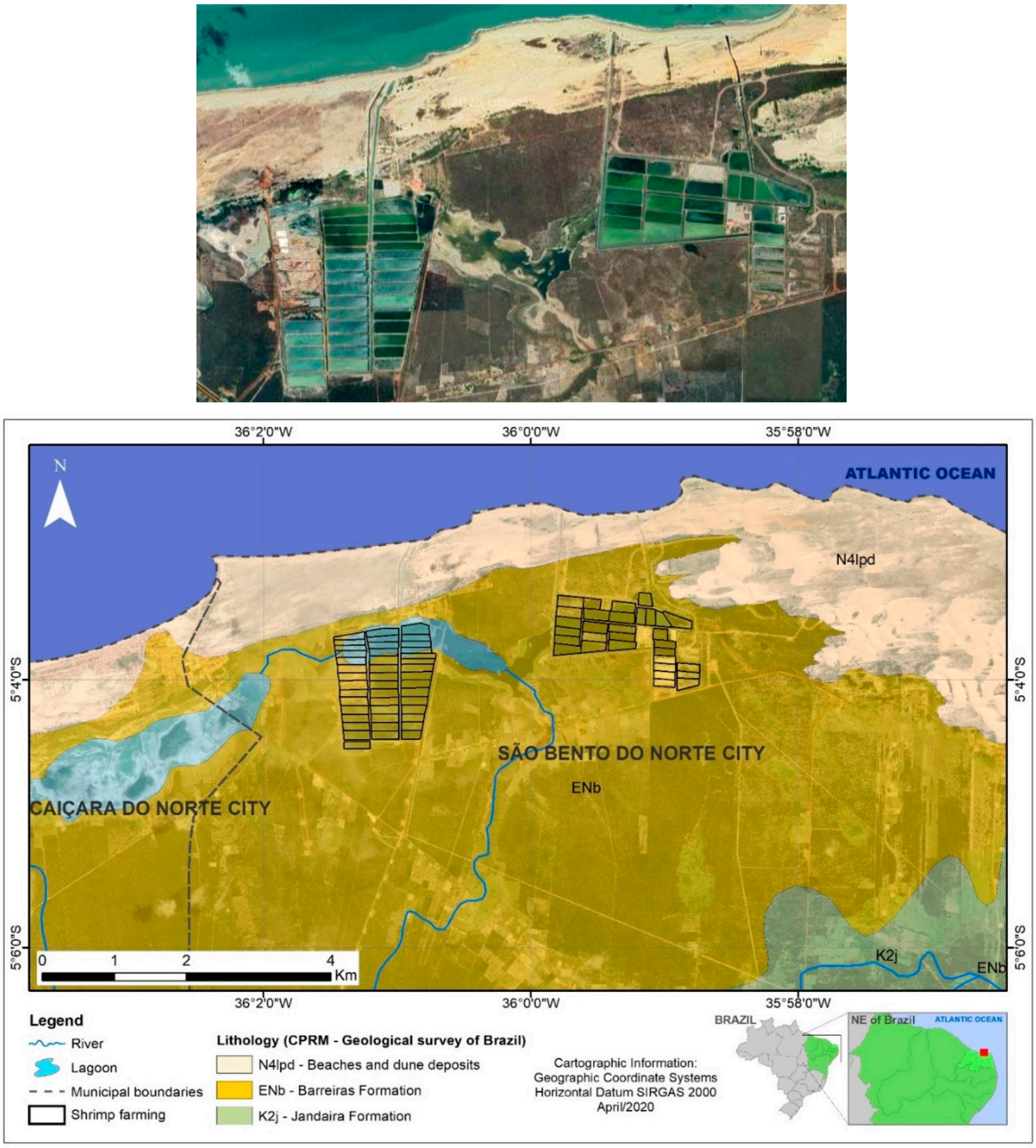

Figure 1. Aerial photography of the study area showing the location of the shrimp ponds and the respective drainage channels to the sea and the coastal environment with dunes and inter-dune lagoons (**upper part**) and a geological sketch of the study area (**lower part**).

The motivation of the study is due to the settlers' report that a large part of the natural vegetation had died, that the soils had become unproductive and that groundwater from the shallow wells used for the water supply was showing a progressive and persistent salinization process.

The salinization process became apparent after the installation close to the boundaries of the settlement of two shrimp culture companies that built several inland ponds. As the surface where the shrimp culture ponds are located at a level slightly higher than sea level, the water inlet is conducted by pumping through pipes from the sea, while the discharge is carried out by gravity directly to the sea through canals.

The climate of the region is tropical, with low variability between the minimum and maximum temperatures throughout the year that remain around 25 ± 1 °C and 30 ± 1 °C, with many hours of solar insolation resulting in high evaporation rates. The main factor causing rainfall is the Intertropical Convergence Zone (ITCZ) in the period from February to May. According to the Brazilian Instituto Nacional de Meteorologia (INMET), the annual rainfall is around 640 mm. The main climatic variation consists of the distribution of rainfall, with an arid period from August to December, while 70% of the annual precipitation is concentrated between February and May. Alongside the long periods of dryness, the region during the last decades has experienced a drastic reduction in annual precipitation, causing the expansion of desertification. The dominant wind direction is NE–SW, with an average annual speed of 6.2 m/s, which can reach speeds of 9 m/s in August. With these climatic characteristics of high temperature, sunstroke, and strong wind, the annual evaporation rate is greater than 1500 mm/year [23].

In addition to its impact on the high evaporation rate, winds are the main responsible for coastal dynamics. Its role is not limited to the generation of waves and, consequently, of sea currents. Subsequently, the sand deposited on the beaches is exposed to air, dried, and moved inland by the winds, resulting in its accumulation in the form of dune fields.

Geomorphologically, the study area is formed by a flattened coastal plain with a topography gently inclined towards the Atlantic Ocean, where beaches and fields of mobile dunes develop. The hydrographic network consists of small intermittent rivers that normally lead to interconnected lagoons, which do not flow directly into the sea. The presence of these lagoons is conditioned by the almost constant existence of dune fields along the coast, which act as natural reservoirs of rain freshwater [24]. Relatively low-relief and clastic, primarily siliciclastic, shorelines are characteristic of the littoral zone. Sand dunes from the Pleistocene to the Holocene, both vegetated and non-vegetated, typically enclose beaches. Tidal flats and lagoons are connected to the sea via tidal inlets, and the region is drained by minor streams and landwards [25].

3. Geological and Hydrogeological Setting

Geologically, the study area is located close to the shore of the Potiguar Basin. The Mesozoic sediments of the basin comprise siliciclastic rocks of the Açu Formation and carbonate rocks of the Jandaíra Formation [26,27], with a thin cover of Paleogene and Neogene age (Barreiras Group) and Quaternary sediments (Figure 1). Carbonate rocks of the Jandaira Formation are found in nearby locations deposited in tidal plains, shallow lagoons, shallow platforms, and deep-sea environments [28]. The Barreiras Formation is a lithostratigraphic unit from Oligocene (Chattian) to Miocene (Tortonian) age [29], distributed discontinuously along the east, northeast and north of the Brazilian coast (>4000 km), formed in a variety of environments, ranging from alluvial fans, fan delta, and meandering river to estuarine setting [30–33].

From the hydrogeological point of view, the Barreiras Aquifer is considered the most important groundwater resource in the coastal regions of NE Brazil. Its lower limit is marked by the top of the non-outcropping Mesozoic carbonate sequence, while its upper limit is occasionally represented by unconsolidated aeolian sediments formed by fine-to-medium sandy sediments, which play an important role in transmitting rainfall that infiltrates and recharges the aquifer.

The recent sandy deposits outcropping in this area are considered an essential aquifer (Dunas Aquifer). The Dunas Aquifer is composed of unconsolidated fine- and medium-grained quartz sand, and has a small thickness, a shallow water level, very low hydrogeological potential and a generally high hydraulic conductivity. The groundwater has electrical conductivity values below 350 µs/cm, reaching a minimum value of 200 µs/cm, and is contemplated as the unique hydrogeological unit with quality groundwater for direct human supply in the municipality of São Bento do Norte/RN [34]. The Barreiras Aquifer is directly connected with the Dunas Aquifer, lithologically is rather heterogeneous, ranging from slightly clayey sandstones and conglomerates to clays [35], has an unconfined to semi-confined behaviour, and is responsible for supplying most of the cities on the state's eastern coastline, including the capital Natal [24]. Accordingly, the Dunas/Barreiras aquifer can be considered as a single integrated system, although each unit has its specific hydrogeological characteristics.

4. Methods

The characterized area is located between the two factories that are involved in the cultivation of shrimp (located at the east and west boundaries of the studied site). Six shallow piezometers (PZ-09, PZ-16, PZ-17, PZ-18, PZ-21, and PZ-22) and the water of the channel that supplies ponds from seawater (C-10) were sampled. Moreover, eight additional piezometers were drilled and sampled to improve the hydrogeological characterization (PZ-10, PZ-11, PZ-12, PZ-13, PZ-14, PZ-15, PZ-19, and PZ-20). The depth of the new and previous piezometers ranges between 2 and 9 m. The drilling diameter was 8 inches and was quickly coated with a 4-inch PVC pipe. The filters were slotted into the PVC structure itself during drilling works varying in length from 1.0 to 2.5 metres. The annular space was filled with gravel and, in the shallowest 0.2 m, fine-grained material from the borehole drilling was used to isolate it. The location of all the piezometers used for the hydrogeological survey is shown in Figure 2.

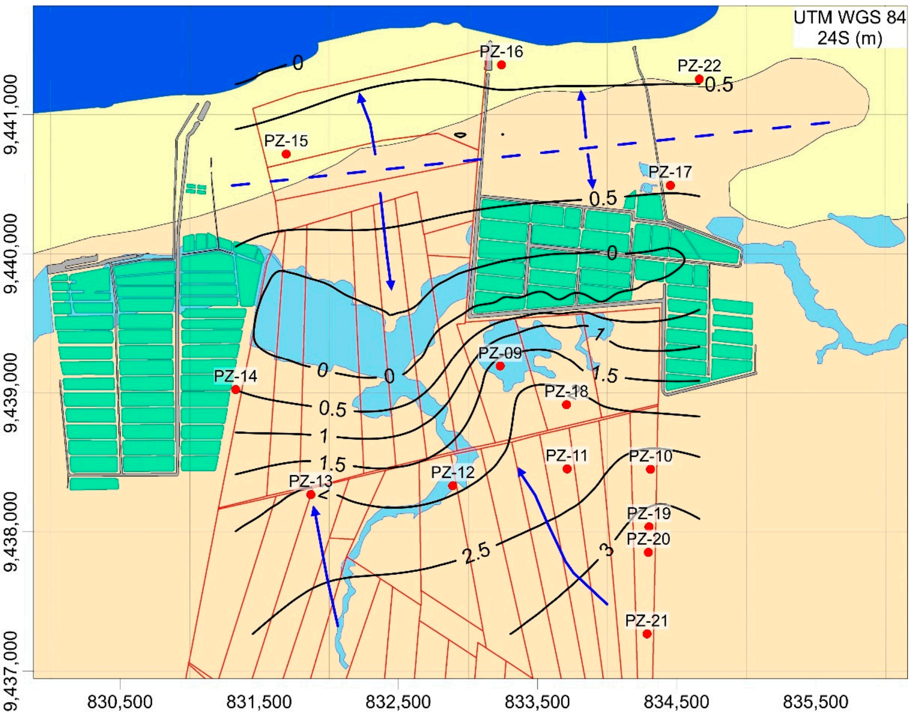

Figure 2. Piezometric map and main groundwater flow (blue arrows) in the studied area. The dashed blue line represents the inferred groundwater watershed in the coastal dune area. Hydraulic heads are presented in metres above mean sea level.

For the positioning of the piezometers and groundwater sample points, high-precision GPS (Geodesic GPS) was used to gather the coordinates and reference elevation as accurately as possible (Table 1). The water table's depth was measured with a standard analogic metre (resolution: ±1 cm).

Polythene bottles with a 1 L capacity were used to collect the samples. Before the collection, bottles were carefully cleaned in the lab using distilled water and diluted HNO_3 acid before being filled with samples. To prevent any potential contamination during bottling, each bottle was washed, stored and transported below 5 °C, and every other precautionary measure was taken [36]. Physico-chemical parameters including pH, temperature (T °C), and electrical conductivity (EC) were measured on-site.

Chemical analyses of major elements were conducted using standard methods [37] at the laboratories of Brazilian Agricultural Research Company EMBRAPA using ICP-AES for Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and Fe^{2+}, ion liquid chromatography for Cl^{-} and $SO_4{}^{2-}$, and automatic volumetric titration for $HCO_3{}^{-}$.

Table 1. Topographic level and water table depth of sampled piezometers.

Well	Elevation (m.a.s.l.)	Water Table Depth (m)
PZ-09	4.5	2.70
PZ-10	8.4	5.56
PZ-11	6.8	4.70
PZ-12	4.7	3.53
PZ-13	8.4	6.20
PZ-14	6.6	2.95
PZ-15	5.0	2.85
PZ-16	0.3	0.2
PZ-17	5.2	4.59
PZ-18	5.2	2.83
PZ-19	10.1	6.93
PZ-20	10.5	7.35
PZ-21	11.5	8.13
PZ-22	6.5	6.20

Careful quality controls were undertaken to obtain a reliable analytical dataset by checking blank samples, calibration standards, and duplicate sub-samples to assess that the analytical error was less than 5%. In addition, analytical precision for measurements of cations and anions, indicated by the ionic balance error (IBE), was computed based on ions expressed in meq/L for each sample as follows:

$$\text{IBE} = [(\Sigma c - \Sigma a)/(\Sigma c + \Sigma a)] \times 100$$

where Σc and Σa are the sums of cations and anions both expressed in (meq/L).

The value of IBE was observed to be below ±4% for all samples analyzed which, given the environmental circumstances at this study site, we see as an acknowledged value.

The software EASYQUIM v5.0 [38] was used to organize and plot the hydrogeochemical data. The software generates the main chemical diagrams such as Piper, to understand the geochemical evolution of groundwater [39] and Schöeller-Berkaloff, to assess the hydrochemical facies of the samples [40].

A third graphical diagram used to interpret the hydrogeochemical data is the Hydrochemical Facies Evolution diagram [41]. The Hydrochemical Facies Evolution (HFE) diagram assesses the salinization of coastal aquifers where the main modifying process is ion exchange. The HFE diagram is useful for highlighting two distinctive facies: the CaCl facies representative of saltwater intrusion and the $NaHCO_3$ facies representative of freshening.

The line of conservative mixing between seawater and freshwater is shown in the EFE diagram. The composition provided by the authors of [42] is used as a default for seawater, while the software chooses the freshwater composition once the set of waters has been stated. The fields of intrusion and freshening phases are determined by the mixing line's position, which is determined by these two fields.

To assess the distribution of hydraulic head charge or piezometric water levels, groundwater electrical conductivity, and major ion data in the studied site, we have used the software Surfer v11 (Golden Software, Golden, CO, USA). The kriging algorithm [43] was selected to interpolate the data, as it has been demonstrated to be well adapted to the interpolation of groundwater water table levels and water quality data [44,45].

5. Results and Discussion

5.1. Groundwater Flow

The assessment of groundwater piezometric levels is one of the most important parameters in the evaluation of groundwater flow of salt intrusion plumes, as they can indicate the direction of the predominant flow lines and their gradient.

Contour plots of the freshwater head, at constant depth and in a horizontal plane, are useful because the flow in isotropic aquifers is normal to these contour lines. The results of the piezometric map and the flow lines of the study area are shown in Figure 2. The distribution of piezometric levels shows two trends. A regional trend from south to north towards the sea is interrupted when reaching the area of the inter-dunes plain. The inter-dunes system is flooded in the rainy season, giving rise to lagoons, and is where the shrimp farms are installed. Near the shoreline, the coastal dune cordon, which can locally reach up to 10 m in height, represents a watershed that drains in both ways, towards the sea and inland towards the inter-dune lagoons. This distribution, where dunes act as a rainwater storage and drainage system, is an effective natural barrier to maintaining the fresh/saltwater balance.

Nevertheless, in the contour map of Figure 2, no variation in the piezometric lines justify clearly the groundwater flow from the ponds. This is because there is a strong gradient produced by the recharge areas located on both sides of the ponds, one in the coastal dunes and the other in the hills. The small gradient existing between the water table and the ponds should be only detected by a high-precision net of piezometers and or/combined with hydrochemical results.

5.2. Hydrogeochemical Data

The groundwater samples were collected on a single campaign carried out during the 2018 dry season. The hydrogeochemical characteristics of the samples have great variability, as applies to a coastal area where freshwater, saltwater, and mixing water converge. The results of the analyses are shown in Table 2.

Table 2. Hydrochemical results of analysis from groundwater samples from piezometers.

Well	HCO_3^-	SO_4^{2-}	Cl^-	Ca^+	Mg^{2+}	Na^+	Fe^{2+}	K^+	EC
	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	µS/cm
PZ-09	3.8	10.6	281.8	34.4	33.8	136.7	0.55	1.8	17,090
PZ-10	3.5	15.1	273.4	38.2	34.3	151.0	0.02	1.5	18,068
PZ-11	4.5	15.0	245.8	30.5	31.3	141.9	0.01	1.3	16,677
PZ-12	1.8	14.9	1,121.0	156.5	162.0	465.8	3.89	5.6	79,855
PZ-13	3.7	3.1	135.7	22.0	17.8	62.1	0.11	2.2	10,421
PZ-14	5.5	23.8	658.9	20.8	63.7	528.0	0.20	12.1	52,330
PZ-15	1.7	0.0	0.8	0.5	0.4	0.4	0.02	0.0	222
PZ-16	4.4	3.7	61.9	3.7	6.0	50.3	0.04	1.2	5927
PZ-17	6.9	0.2	4.2	2.0	1.3	2.3	0.84	0.9	944
PZ-18	2.8	3.0	66.3	7.1	8.3	40.4	0.01	1.3	5530
PZ-19	7.6	9.4	149.5	21.2	21.5	83.9	0.03	1.5	11,825
PZ-20	3.0	6.0	55.1	8.0	7.5	34.8	0.75	1.1	5232
PZ-21	15.0	11.1	181.9	27.4	25.1	103.5	0.04	1.5	13,622
PZ-22	2.2	0.0	0.6	0.8	0.4	0.4	0.00	0.0	261
C-10	3.0	31.3	628.6	32.4	32.8	496.9	0.01	9.2	48,370

The Piper diagram gives significant information that allows us to discriminate between separate clusters (groups) of samples. The diagram shows that most of the groundwater samples analyzed fall in the field of the Calcium-Sodium Chloride type, except for samples from piezometers PZ-15 and PZ-17 that visibly stand out of this composition and can be classified as of the Magnesium Bicarbonate type (Figure 3). This method is very well suited for discriminating between hydrochemical facies because ion content is given as a percentage of milliequivalents, but Piper's diagram is not useful for describing water salinity concentrations, because it does not consider the water concentrations.

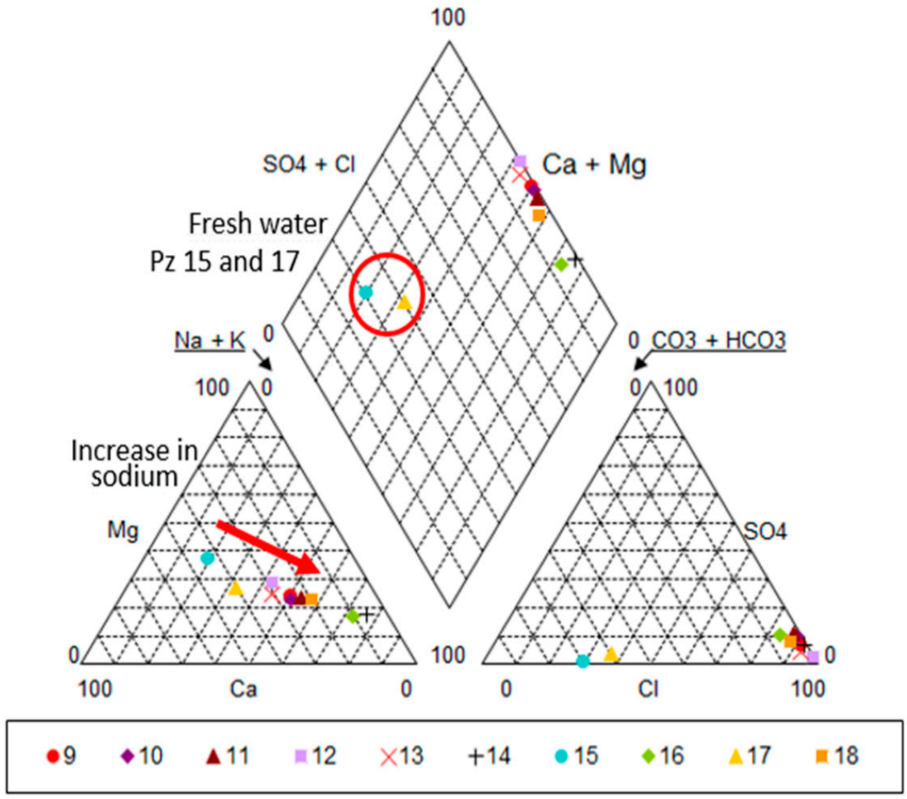

Figure 3. Piper trilinear diagram showing the different hydrogeochemical facies, where the freshwaters of the PZ-15 and PZ-17 piezometers located next to the coastline and further away from the aquaculture ponds are well isolated (within the red circle area).

In the Schoeller diagram, we have differentiated two different water facies. Water samples from coastal dunes (PZ-15 and PZ-17) could be classified as bicarbonate calcium facies and show values lower than 10 meq/L of the major ions plotted and values below 1 meq/L of SO_4^{2-}. The other water samples could be classified as chloride sodium facies and have concentrations of [Cl^-] and [Na^+] above 10 meq/L. There is a progressive increase in these values from the coastline (PZ-16) towards inland control points (PZ-12) (Figure 4).

The HFE diagram clusters the water of piezometers PZ-22, PZ-15 and PZ-17 (located close to the seashore) on the HCO3 zone indicating the effect of refreshing. Conversely, samples from piezometers located inland show values in the MixNa–Na range, indicating saltwater intrusion (Figure 5).

The main goal is to characterize the origin and distribution of a salinization process, and the first and key indicator of interest is the electrical conductivity of groundwater [46,47]. In the study area, as expected, the electrical conductivity values of groundwater have a high range of variation. The electrical conductivity of groundwater samples measured in the piezometers distributed in the aquifer show values ranging from a minimum of 222 µS/cm to a maximum of 79,855 µS/cm. The isolines resulting from the interpolation of sparse data points are shown in Figure 6. Unexpectedly, the lowest values of electrical conductivity and salinity are found on the PZ-15 piezometer located very close to the coastline over the dunes. In opposition, the highest values of electrical conductivity and salinity are found on the PZ-12 piezometer located in the central area of the study area between the two shrimp factories and almost 3 kilometres away from the sea. Therefore, the distribution of salinity does not appear to be directly related to a natural marine intrusion phenomenon, as freshwater piezometers are located near the coast, while the highest salinity is in an area between the shrimp culture ponds.

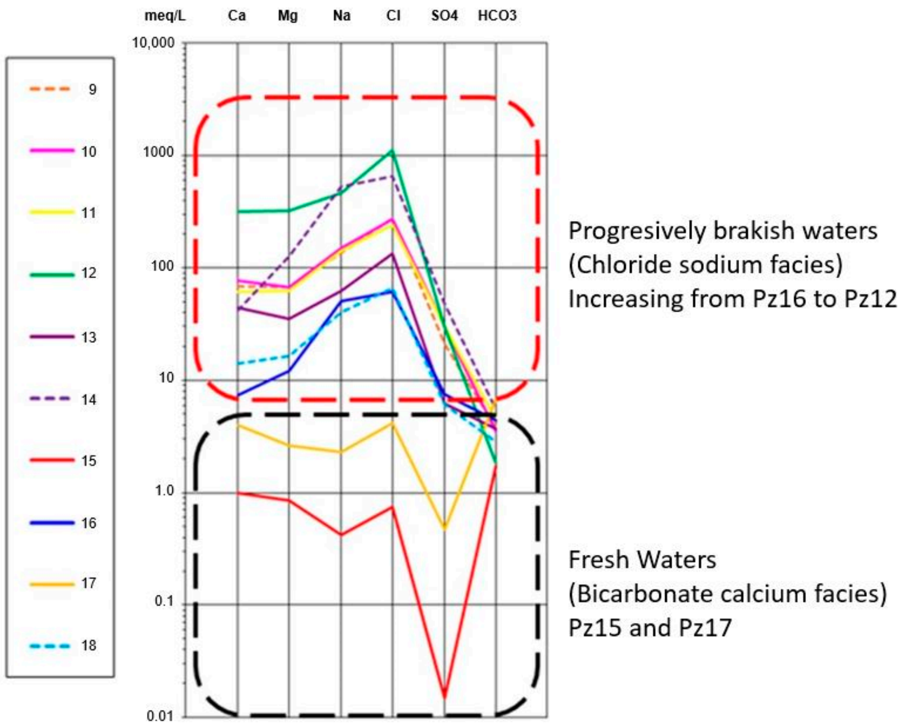

Figure 4. Schoeller diagram showing the different behaviour of the hydrochemical facies, including an increase in chloride and sodium of the salinized samples, and, conversely, the low sulphate content of the natural freshwater samples from the dunes aquifer.

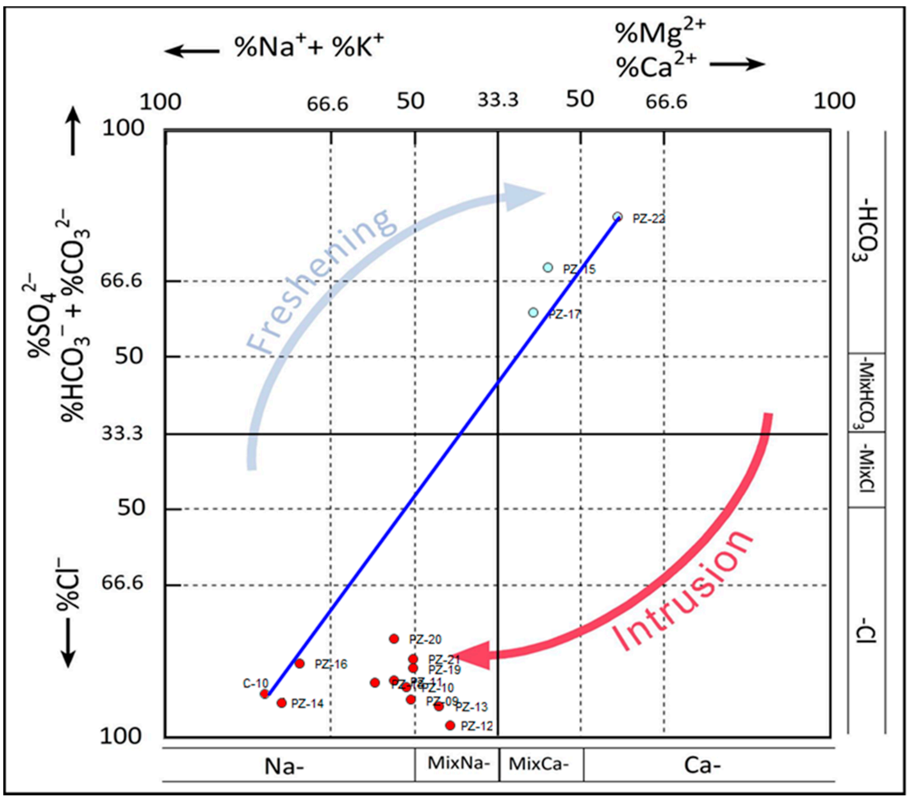

Figure 5. Representation of groundwater samples in the HFE diagram showing the effect of refreshing on piezometers PZ-22, PZ-15 and PZ-17 located close to the seashore. Conversely, samples from piezometers located inland show saltwater intrusion.

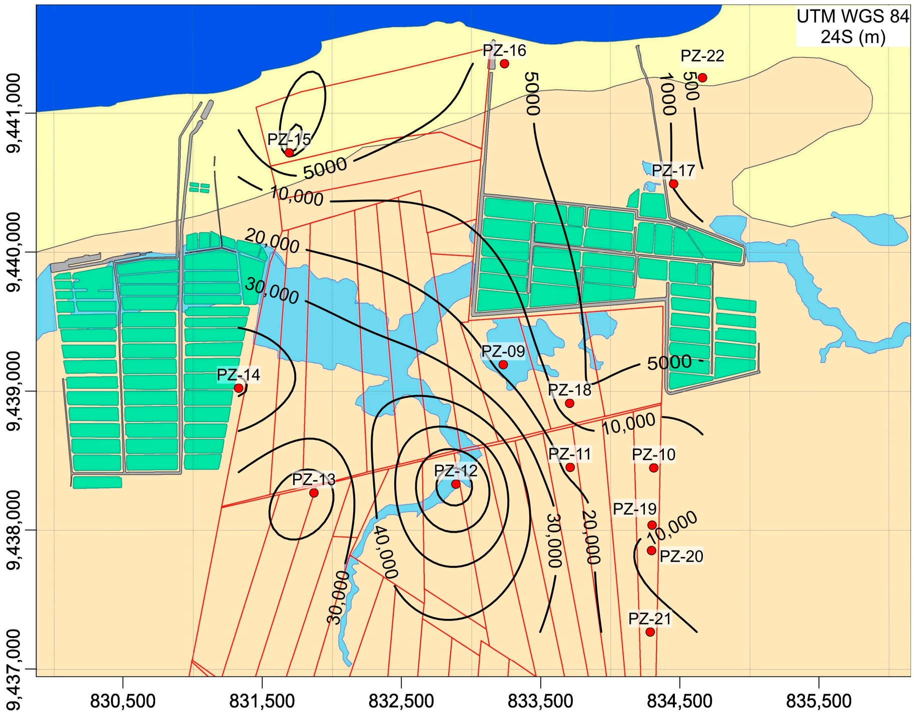

Figure 6. Map showing the distribution of the electrical conductivity of groundwater from water samples taken at the control piezometers. The area of the highest salinity is located between the ponds of the two aquiculture factories and decreases towards the coast. Isoline values are in µS/cm.

The hydrochemical concentration of groundwater also shows significant variability. Total dissolved solids (TDS) reasonably fluctuate similarly to electrical conductivity, from a minimum of 725 mg/L on the PZ-15 to a maximum of 62,078 mg/L on the PZ-14 piezometer, with a similar spatial distribution.

In Figure 4, Schoeller's diagram clearly shows the low sulphate content of groundwater samples from the dune aquifer. A better explanation of the origin and evolution of concentrations in sulphate can be seen in the form of a map depicting their distribution in the form of isolines. The distribution of the sulphate content of groundwater shows that the highest concentrations are in the central sector between the two shrimp factories and that the increase comes laterally from each of them (Figure 7).

The life and growth of shrimp may be adversely affected by large ion imbalances, even though natural marine water contains a salinity that is suitable for shrimp culture [48]. Farmers apply two fertilizers, potassium chloride and potassium magnesium sulphate, to add potassium ions to the pumped ocean water and salty water (Figure 7).

Shrimp production and survival were significantly increased by a single application of these fertilizers before or shortly after stocking ponds, with potassium accounting for the majority of the benefits [49].

Moreover, the joint interpretation of groundwater flow and hydrochemical results shows that the diffusion of the salty water of the ponds to the Dunas Aquifer freshwater is the contamination mechanism as the ponds are not properly waterproofed. The water level of the ponds is higher than the aquifer hydraulic head level and the coastal dunes act as a hydraulic barrier preventing seawater intrusion.

The study demonstrated that the salinization of groundwater around the shrimp factories of the Baixa de Queixaba sector in the state of Rio Grande do Norte State (Brazil) has its origin in the direct infiltration of seawater from the ponds and is not the result of a natural process of marine intrusion.

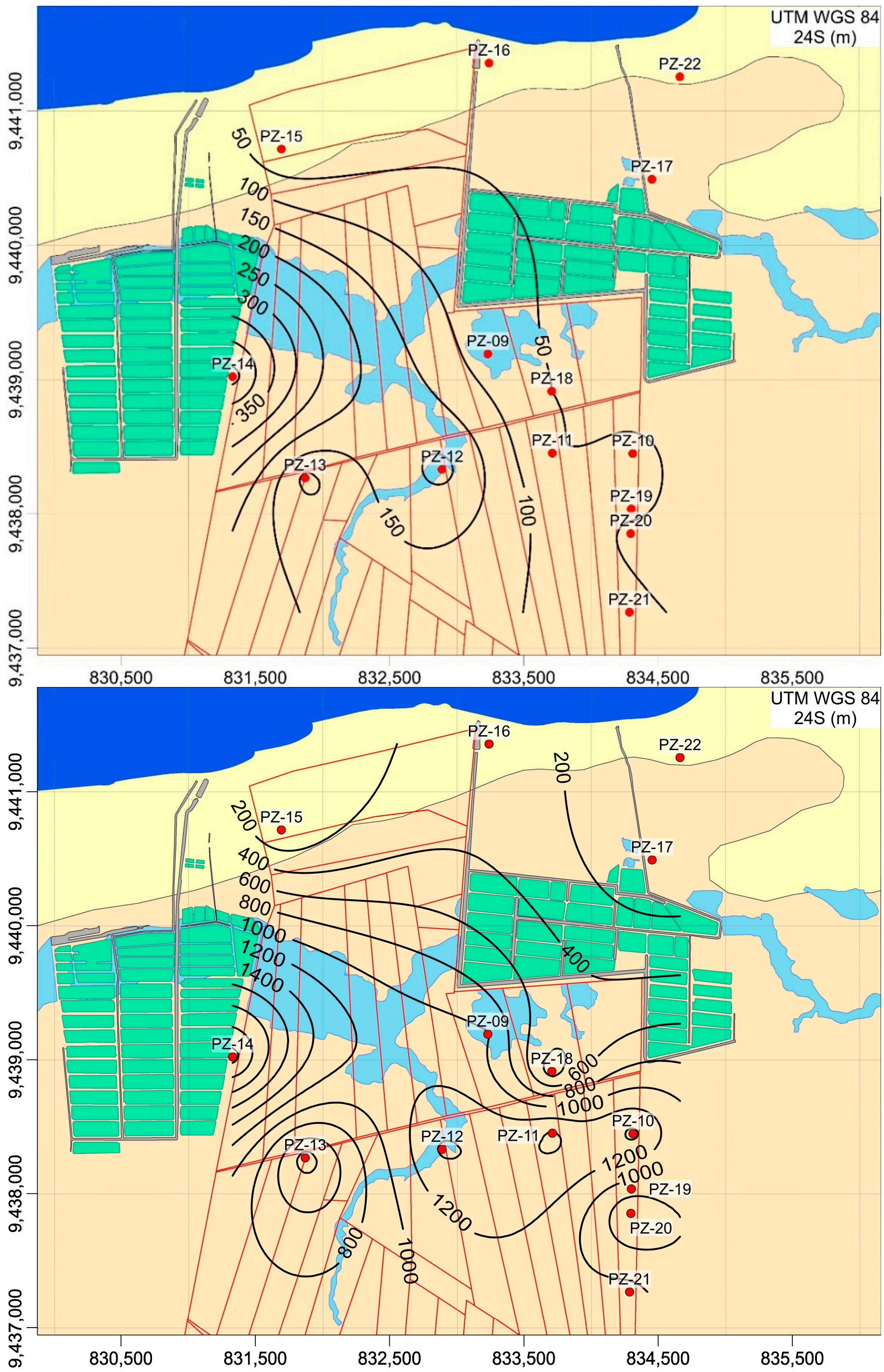

Figure 7. Map showing the distribution of potassium content of groundwater (**upper part**) and sulphate content (**lower part**) from water samples taken at the control piezometers. The highest concentration of potassium and sulphate is in piezometer PZ-14 located close to the western ponds and there is also an increasing trend from the south to the easter ponds. Isoline values are in mg/L.

6. Conclusions

The integration of hydrogeological and hydrogeochemical survey results has made it possible to establish that the origin of groundwater pollution in the studied area is caused by saltwater percolation from shrimp farms. Information derived from the piezometric map shows that rainwater recharge in the frontal dunes acts as a dynamic barrier to seawater intrusion, while saltwater flow must come from the ponds. Hydrochemical data also corroborate this interpretation, since the piezometers closest to the coast are those with the lowest salinization in terms of both electrical conductivity and concentration of chloride and sodium in groundwater. Another factor that reinforces this interpretation is that the plumes of sulphates and potassium escape from the edges of ponds and are added to natural seawater to increase the production and survival of shrimp larvae.

The joint use of both techniques has shown to be a cost-effective and low-intrusive methodology, which can be applied in other areas with similar environmental concerns; the results of this research have also highlighted the vulnerability of coastal aquifers affected by poorly planned and poorly managed human activities. In particular, the implementation of shrimp cultivation factories, which in principle could mean a socio-economic development for the native population, can cause a serious environmental impact, which is sometimes irreversible or comes with a very difficult and costly recovery process.

Sustainable shrimp farming requires the development of methodologies that allow the efficient design of production ponds and legal measures that require impact control through characterization procedures such as those carried out in this study.

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References

1. Páez-Osuna, F. The environmental impact of shrimp aquaculture: A global perspective. *Environ. Pollut.* **2001**, *112*, 229–231. [CrossRef] [PubMed]
2. Sanz, J.; Suescun, J.; Molist, J.; Rubio, F.; Mujeriego, R.; Salgado, B. Reclaimed water for the Tarragona petrochemical park. *Water Supply* **2014**, *15*, 308–316. [CrossRef]
3. Yakovenko, V.; Shadrin, N.; Anufriieva, E. The Prawn Palaemon adspersus in the Hypersaline Lake Moynaki (Crimea): Ecology, Long-Term Changes, and Prospects for Aquaculture. *Water* **2022**, *14*, 2786. [CrossRef]
4. Anufriieva, E. V How can saline and hypersaline lakes contribute to aquaculture development? A review. *J. Oceanol. Limnol.* **2018**, *36*, 2002–2009. [CrossRef]
5. Hossain, M.S.; Uddin, M.J.; Fakhruddin, A.N.M. Impacts of shrimp farming on the coastal environment of Bangladesh and approach for management. *Rev. Environ. Sci. Bio/Technol.* **2013**, *12*, 313–332. [CrossRef]
6. HEIN, L. Toward Improved Environmental and Social Management of Indian Shrimp Farming*. *Environ. Manag.* **2002**, *29*, 349–359. [CrossRef]
7. Primavera, J.H. Overcoming the impacts of aquaculture on the coastal zone. *Ocean Coast. Manag.* **2006**, *49*, 531–545. [CrossRef]
8. Paul, B.G.; Vogl, C.R. Impacts of shrimp farming in Bangladesh: Challenges and alternatives. *Ocean Coast. Manag.* **2011**, *54*, 201–211. [CrossRef]
9. Hidayati, N.V.; Prudent, P.; Asia, L.; Vassalo, L.; Torre, F.; Widowati, I.; Sabdono, A.; Syakti, A.D.; Doumenq, P. Assessment of the ecological and human health risks from metals in shrimp aquaculture environments in Central Java, Indonesia. *Environ. Sci. Pollut. Res.* **2020**, *27*, 41668–41687. [CrossRef]
10. Ahmed, Z.; Ambinakudige, S. Does land use change, waterlogging, and salinity impact on sustainability of agriculture and food security? Evidence from southwestern coastal region of Bangladesh. *Environ. Monit. Assess.* **2022**, *195*, 74. [CrossRef]
11. Bijith, P.; Ramith, M.; Megha, T.; Shimod, K.P.; Pradeep, M.N. Shrimp farms as a threat to mangrove forests in Kannur district of Kerala, India. *Wetl. Ecol. Manag.* **2022**, *30*, 1281–1289. [CrossRef]
12. Neiland, A.E.; Soley, N.; Varley, J.B.; Whitmarsh, D.J. Shrimp aquaculture: Economic perspectives for policy development. *Mar. Policy* **2001**, *25*, 265–279. [CrossRef]
13. Lassen, T.J. Environmental extremes versus sustainable policies in aquaculture. *World Aquac.* **1997**, *28*, 49–51.
14. Gusmawati, N.; Soulard, B.; Selmaoui-Folcher, N.; Proisy, C.; Mustafa, A.; Le Gendre, R.; Laugier, T.; Lemonnier, H. Surveying shrimp aquaculture pond activity using multitemporal VHSR satellite images—Case study from the Perancak estuary, Bali, Indonesia. *Mar. Pollut. Bull.* **2018**, *131*, 49–60. [CrossRef]
15. Harkes, I.H.T.; Drengstig, A.; Kumara, M.P.; Jayasinghe, J.M.P.K.; Huxham, M. Shrimp aquaculture as a vehicle for Climate Compatible Development in Sri Lanka. The case of Puttalam Lagoon. *Mar. Policy* **2015**, *61*, 273–283. [CrossRef]

16. Elwin, A.; Jintana, V.; Feola, G. Characterizing shrimp-farm production intensity in Thailand: Beyond technical indices. *Ocean Coast. Manag.* **2020**, *185*, 105019. [CrossRef]
17. Dorber, M.; Verones, F.; Nakaoka, M.; Sudo, K. Can we locate shrimp aquaculture areas from space?—A case study for Thailand. *Remote Sens. Appl. Soc. Environ.* **2020**, *20*, 100416. [CrossRef]
18. Jablonski, S.; Filet, M. Coastal management in Brazil—A political riddle. *Ocean Coast. Manag.* **2008**, *51*, 536–543. [CrossRef]
19. Valenti, W.C.; Barros, H.P.; Moraes-Valenti, P.; Bueno, G.W.; Cavalli, R.O. Aquaculture in Brazil: Past, present and future. *Aquac. Reports* **2021**, *19*, 100611. [CrossRef]
20. Evans, J. Brazilian Shrimp Farmers Eye New Horizons 2023, 4. Available online: https://www.globalseafood.org/advocate/brazilian-shrimp-farmers-eye-new-horizons/ (accessed on 16 June 2024).
21. Callaghan, D.P.; Bouma, T.J.; Klaassen, P.; van der Wal, D.; Stive, M.J.F.; Herman, P.M.J. Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance of waves and tidal flows. *Estuar. Coast. Shelf Sci.* **2010**, *89*, 73–88. [CrossRef]
22. Roversi, F.; van Maanen, B.; Colonna Rosman, P.C.; Neves, C.F.; Scudelari, A.C. Numerical Modeling Evaluation of the Impacts of Shrimp Farming Operations on Long-term Coastal Lagoon Morphodynamics. *Estuaries Coasts* **2020**, *43*, 1853–1872. [CrossRef]
23. da Silva, V. de P.R. On climate variability in Northeast of Brazil. *J. Arid Environ.* **2004**, *58*, 575–596. [CrossRef]
24. Tabosa, W.F. Dinâmica Costeira da Região de São Bento do Norte e Caiçara do Norte—RN. MSc Thesis, Universidade Federal do Rio Grande do Norte, Natal, Brasil, 2000.
25. Bezerra, F.H.R.; Barreto, A.M.F.; Suguio, K. Holocene sea-level history on the Rio Grande do Norte State coast, Brazil. *Mar. Geol.* **2003**, *196*, 73–89. [CrossRef]
26. Neto, P.; Soares, U.; Silva, J.G.; Roesner, E.H.H.; Florencio, C.P.P.; Souza, C.A.V.A.V.; Neto, O.C. Bacia Potiguar. *Bol. Geociências Petrobras* **2007**, *15*, 357–369.
27. Melo, A.H.; Andrade, P.R.O.; Magalhães, A.J.C.; Fragoso, D.G.C.; Lima-Filho, F.P. Stratigraphic evolution from the early Albian to late Campanian of the Potiguar Basin, Northeast Brazil: An approach in seismic scale. *Basin Res.* **2020**, *32*, 1054–1080. [CrossRef]
28. Santos Filho, M.A.B.; Piovesan, E.K.; Fauth, G.; Srivastava, N.K. Paleoenvironmental interpretation through the analysis of ostracodes and carbonate microfacies: Study of the Jandaíra Formation, Upper Cretaceous, Potiguar Basin. *Brazilian J. Geol.* **2015**, *45*, 23–34. [CrossRef]
29. Nogueira, A.C.R.A.A.E.; Amorim, K.B.; Góes, A.M.; Truckenbrodt, W.; Petri, S.; Nogueira, A.C.R.A.A.E.; Bandeira, J.; Soares, J.L.; Baía, L.B.; Imbiriba Júnior, M.; et al. Upper Oligocene-Miocene deposits of Eastern Amazonia: Implications for the collapse of Neogene carbonate platforms along the coast of northern Brazil. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2021**, *563*, 110178. [CrossRef]
30. Rossetti, D.F. Late Cenozoic sedimentary evolution in northeastern Pará, Brazil, within the context of sea level changes. *J. South Am. Earth Sci.* **2001**, *14*, 77–89. [CrossRef]
31. De Araújo, V.D.; Reyes-Peres, Y.A.; Lima, R.d.O.; Pelosi, A.P.d.M.R.; Menezes, L.; Córdoba, V.C.; Lima-Filho, F.P. Fácies e sistema deposicional da formação barreiras na região da Barreira do Inferno, Litoral Oriental do Rio Grande do Norte. *Geol. USP. Série Científica* **2006**, *6*, 43–49. [CrossRef]
32. Rossetti, D.F.; Bezerra, F.H.R.; Dominguez, J.M.L. Late Oligocene–Miocene transgressions along the equatorial and eastern margins of Brazil. *Earth-Sci. Rev.* **2013**, *123*, 87–112. [CrossRef]
33. Rodríguez-Escales, P.; Canelles, A.; Sanchez-Vila, X.; Folch, A.; Kurtzman, D.; Rossetto, R.; Fernández-Escalante, E.; Lobo-Ferreira, J.P.; Sapiano, M.; San-Sebastián, J.; et al. A risk assessment methodology to evaluate the risk failure of managed aquifer recharge in the Mediterranean Basin. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 3213–3227. [CrossRef]
34. Vasconcelos, S.M.S.; Teixeira, Z.A.; Alvez, J.N. Caracterização do Aquífero Jandaíra, porção situada no estado do Ceará, Brasil. *Rev. Geol.* **2010**, *23*, 50–60.
35. Lucena, L.R.F.; Cabral, J.B.P.; Becegato, V.A. Aspectos hidroquímicos do aqüífero Barreiras na área da Bacia do rio Pirangi-RN/Brasil e adequações para uso humano e irrigação. *Geoambiente On-Line* **2004**, *1*, 1–14. [CrossRef]
36. Mondal, N.C.; Singh, V.P.; Singh, V.S.; Saxena, V.K. Determining the interaction between groundwater and saline water through groundwater major ions chemistry. *J. Hydrol.* **2010**, *388*, 100–111. [CrossRef]
37. Clesceri, L.S.; Greenberg, A.E.; Eaton, A.D. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; APHA American Public Health Association: Washington, DC, USA, 1998.
38. Vazquéz-Suñe, E.; Serrano-Juan, A. *EasyQuim*; Institute of Environmental Assessment and Water Research: Barcelona, Spain, 2012.
39. Piper, A.M. A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Trans. Am. Geophys. Union* **1944**, *25*, 914–928. [CrossRef]
40. Schoeller, H. Qualitative Evaluation of Ground Water Resources. In *Water Resource Series No. 33*; UNESCO: Paris, France, 1967; pp. 44–52.
41. Giménez-Forcada, E. Dynamic of sea water interface using hydrochemical facies evolution diagram. *Ground Water* **2010**, *48*, 212–216. [CrossRef]
42. Turekian, K.K. *Oceans (Foundations of Earth Science Series)*, 2nd ed.; Pearson College: Upper Saddle River, NJ, USA, 1976; ISBN 978-0136304180.
43. Matheron, G. Traite de Geostatistique Apliquee. In *Tome I. Memoires Bureau de Recherches Geologiques et Minieres*; Editions Bureau de Recherche et Minieres: Paris, France, 1962.

44. Belkhiri, L.; Tiri, A.; Mouni, L. Spatial distribution of the groundwater quality using kriging and Co-kriging interpolations. *Groundw. Sustain. Dev.* **2020**, *11*, 100473. [CrossRef]
45. Nistor, M.M.; Rahardjo, H.; Satyanaga, A.; Hao, K.Z.; Xiaosheng, Q.; Sham, A.W.L. Investigation of groundwater table distribution using borehole piezometer data interpolation: Case study of Singapore. *Eng. Geol.* **2020**, *271*, 105590. [CrossRef]
46. Custodio, E.; Bruggerman, G.A. *Groundwater Problems in Coastal Areas*; UNESCO: Paris, France, 1987; ISBN 978-92-3-102415-3.
47. Kovalevsky, V.; Kruseman, G.; Rushton, K. *Groundwater Studies: An International Guide for Hydrogeological Investigations*; UNESCO: Paris, France, 2004; ISBN 92-9220-005-4.
48. Boyd, C.A.C.E.; Boyd, C.A.C.E.; Rouse, D.B. Potassium budget for inland, saline water shrimp ponds in Alabama. *Aquac. Eng.* **2007**, *36*, 45–50. [CrossRef]
49. McNevin, A.A.; Boyd, C.E.; Silapajarn, O.; Silapajarn, K. Ionic Supplementation of Pond Waters for Inland Culture of Marine Shrimp. *J. World Aquac. Soc.* **2004**, *35*, 460–467. [CrossRef]