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Saline Intrusion in Puerto Vallarta's Freshwater Sources: Hydrogeophysical Analysis in a Mexican Coastal City

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ABSTRACT

This research addresses potential saline intrusion in a coastal tourist city such as Puerto Vallarta, a significant tourist hub on the Mexican Pacific coast, where water production and consumption are close to the equilibrium point. Overexploitation and proximity to the ocean threaten its sources of supply. The objective is to explore the possible saline intrusion that occurs when salt water mixes with groundwater sources for human consumption. Various factors, such as the overexploitation of aquifers, highlight the need for effective management of water resources in coastal tourist cities due to the growing pressure on this resource by the population and visitors. The study commences with an exploratory analysis of a water extraction source located in the Pitillal River basin, with suspicions of elevated chloride levels. Employing hydrogeophysical analysis to measure the electrical resistivity of subsurface materials, the research determines their characteristics and distribution. Results indicate low resistivity at 14-20 meters depth, associated with water containing chlorides. On-site verification reveals a concentration of 301 mg/L of dissolved chlorides, surpassing the recommended 250 mg/L for human consumption according to the World Health Organization and the Official Mexican Standard. Therefore, ongoing studies in other nearby sources are crucial to assess contamination risks and enhance strategies for water use efficiency or explore new sources, ensuring sustainability and water security in the region.

1. INTRODUCTION

One of the most vital resources on the planet, essential for the survival of all living beings, is water. Crucial element for a wide variety of human activities, such as industry, livestock, agriculture and energy generation. Globally, access to it is increasingly difficult due to pollution, droughts are an increasingly growing problem. This has led to the need to develop sustainable technologies and practices for water management, the formulation of policies and strategies in favor of conservation and its responsible use. In summary, water is an essential resource for life and human development, and its importance in today's world cannot be underestimated [1].

In Mexico, the socio-natural cycle of water faces a serious threat caused by changes in land use, economic activities and urbanization processes. The advanced deterioration of hydrological basins and aquifers in the country represents a significant risk to human health, economic production and the capacity to adapt to climate change [2].

For almost six decades, Puerto Vallarta, as a tourist destination, has experienced continuous growth and has gone through various phases in its development process. It has transformed from its roots as a fishing community to consolidate itself as one of the most popular coastal destinations in the Mexican Pacific, being a place of choice for foreign tourists looking for sun and beach vacations [3].

Puerto Vallarta, together with Bahía de Banderas, forms a metropolitan area (Figure 1). This situation has led to the joint recognition of Puerto Vallarta and Bahía de Banderas as one of the primary beach tourist destinations on the Pacific coast of Mexico, ranking second nationwide after Cancún. Annually, the region welcomes approximately six million tourists [4]. According to the Population and Housing Census, Puerto Vallarta had 291,839 inhabitants in 2020 [5].

With the growth of the population of Puerto Vallarta, comes a parallel increase between urban expansion and tourism infrastructure, which has generated a greater demand for essential services, including the supply of drinking water. This growing demand for the vital liquid ends up overexploiting the supply sources, which, with the proximity to the ocean, can generate an intrusion of saline water into the coastal aquifers. Puerto Vallarta managed 98.80% coverage of this vital liquid for the population with a per capita supply of 252 liters per capita per day (December 2020) [6].

Saline intrusion is a phenomenon that affects many coastal cities worldwide, referring to the entry of saltwater into freshwater aquifers due to various factors. This issue can have severe consequences for freshwater supply and the environment in these areas.

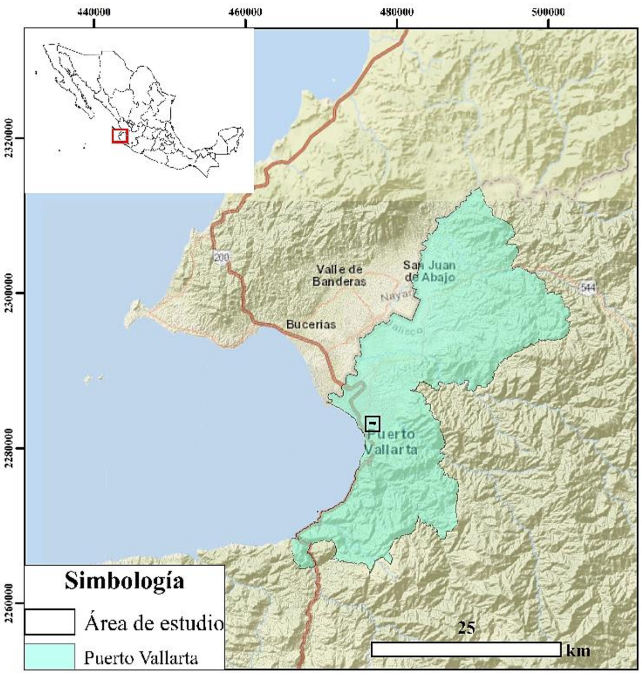

Figure 1. Puerto Vallarta, Jalisco

Saline intrusion can be caused by rising sea levels due to climate change, overexploitation of aquifers, groundwater extraction near the coast, and the construction of coastal structures such as dikes and dams [7].

Saline intrusion can contaminate groundwater sources, rendering water non-potable and expensive to treat for human consumption [8]. This can lead to a water supply crisis in coastal cities. As salinity accumulates in coastal aquifers, the amount of usable freshwater decreases, potentially causing water shortages in communities dependent on these sources for drinking water. Additionally, it can harm local flora and fauna [9].

Cities such as Miami in the United States [10], various locations in Mexico with 18 aquifers [11], and Bangkok in Thailand have experienced saline intrusion issues due to their coastal location or overexploitation of their aquifers.

Moreover, saline intrusion poses a public health risk, as the World Health Organization (WHO) [12] and the Official Mexican Standard NOM-127 [13] establish that the maximum salinity level for drinking water for human consumption is 250 milligrams per liter (mg/L). When the salinity level of drinking water exceeds this value, the water is considered contaminated and unsuitable for human consumption.

Since the 1970s, Puerto Vallarta has maintained sustained population growth, which is why the drinking water operator has carried out hydraulic infrastructure works to serve the population. In the 90's, several deep drillings were carried out to access the available sources of groundwater, guaranteeing population demand. Therefore, Seapal has an annual concession of 47,703,900 cubic meters of groundwater, which represents 80% of the total water consumed, located mainly in the areas near the Ameca and Pitillal Rivers [14]. However, recent studies have estimated that by 2030 the equilibrium point between production and consumption will be reached [15]. If the increase in demand continues, and the same infrastructure for management continues to be used, water levels could be altered to negative recharge, generating water stress.

Currently, the actions carried out by the drinking water operating agency are to ensure the recharge of the aquifers, avoiding overexploitation. It is essential to maintain the optimal levels of its extraction sources to ensure its sustainable use, since its proximity to the sea increases the risk of saline intrusion, contaminating the sources of water collection and extraction, which would worsen the future scenario.

Access to potable water, in addition to being one of the main indicators of human development, is also considered a fundamental aspect of tourist activities, as it can influence the choice of tourist destinations [16]. It is of vital importance to meet the demand for potable water and anticipate future consumption by potable water utilities. This allows them to optimize water management and, in turn, meet the qualifications and sustainability requirements of the sector [17].

In recent years, there have been suspicions of chloride presence in the well water in Puerto Vallarta, primarily in the wells located in the Pitillal River basin, which has raised concerns for the potable water utility (Figure 2).

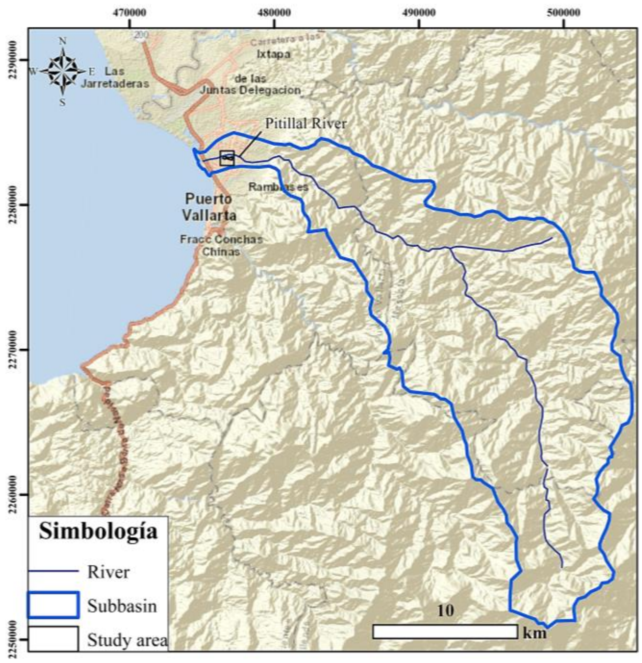

Figure 2. Pitillal River hydrological basin

The possible presence of chlorides in some wells in Puerto Vallarta may result from the infiltration of saline water from the sea through the aquifer and excessive groundwater extraction in certain areas. This leads us to investigate the potential risk of saline intrusion in different extraction wells located in the Pitillal River basin through hydrogeophysical resistivity studies of the terrain, with particular focus on well No. 8 (Figure 2), where the presence of chlorides is suspected.

Saline intrusion represents a significant threat due to the interaction of two key factors: the growing demand for water associated with population and tourism growth, and the city's proximity to the ocean. The increase in demand for water, mainly to supply the growing local population and the millions of tourists who visit the region annually, puts pressure on freshwater sources.

Given the importance of Puerto Vallarta as a tourist destination, saline intrusion not only threatens the availability of drinking water, but also puts at risk the quality of the beaches and the natural environment, fundamental elements for tourist attraction.

The rapid growth of the population and tourism infrastructure in Puerto Vallarta intensifies the urgency of addressing this problem. Salt intrusion not only compromises public health by contaminating drinking water supplies, but also threatens the sustainability of the tourism industry, a key pillar of the local economy. Sustainable water management therefore becomes an immediate priority to ensure the balanced and sustainable development of Puerto Vallarta in the future.

2. MATERIALS AND METHODS

To achieve the objective of this study, Electrical Resistivity Tomography (ERT) was employed, which is a highly useful geophysical technique for investigating the distribution of electrical resistivity in the subsurface. It serves as an effective tool for assessing the presence of chlorides in water wells, as chloride levels are often associated with low electrical resistivity.

For this purpose, a resistivity meter (SYSCAL, direct current by IRIS INSTRUMENTS) was utilized. The multi-node, multi-electrode acquisition system comprises 10 channels, a current transmitter powered by a power converter, allowing the generation of substantial voltage differentials from a 12-volt battery [18].

Furthermore, an in-situ water sample was collected, and a digital meter was used to determine its density, dissolved chlorides, and conductivity.

2.1 Hydrogeophysical campaign

Study Area: The location of well No. 8, where the presence of chlorides was suspected, was determined as the focal point of the study. The extension of the study area was planned in relation to this well, which is located 70 meters parallel to the Pitillal River (Figure 3).

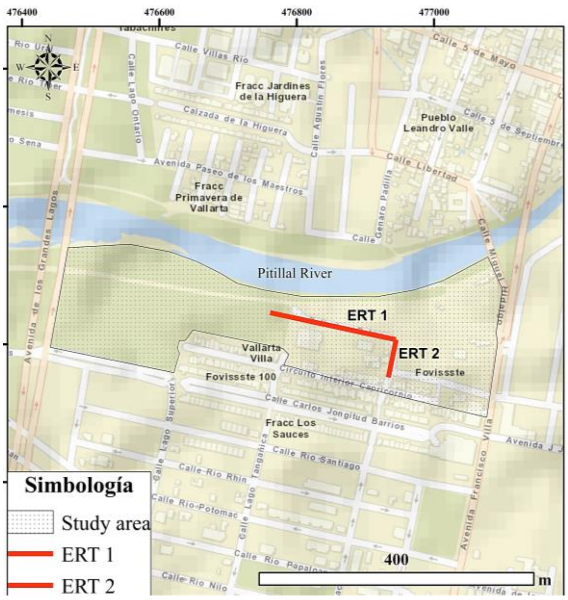

Figure 3. Study area

A suitable electrode arrangement was chosen, using a Wenner arrangement. The choice of configuration considered the desired depth and resolution, since it minimizes interference and improves sensitivity to variations in resistivity.

Two lines of perpendicular profiles were implemented, because this arrangement of electrodes in a perpendicular configuration in electrical tomography is chosen to maximize the vertical resolution, generating 2D resistivity images, clearly evidencing the site studied, improving sensitivity to resistivity variations. electrical and facilitate the interpretation of the results. The line for Electrical Resistivity Tomography 1 (ERT 1) was oriented from East to West, parallel to the Pitillal River and the line for Electrical Resistivity Tomography 2 (ERT 2) was located from North to South, perpendicular to ERT 1. Allowing the flow of groundwater to be followed, identifying possible recharge routes or areas with high electrical conductivity associated with the presence of low resistivity saline water.

The lengths of these lines were 180 meters for ERT1 and 50 meters for ERT2, with a Wenner geometric device and electrode separation varying between 8 meters and 5 meters, with the objective of deeply exploring well No. 8 (Figure 3).

Techniques such as electrical resistivity are affected by environmental conditions. Dry conditions are preferable for more accurate results. In dry conditions, the soil tends to have a more stable and homogeneous electrical resistivity, facilitating the interpretation of data and improving measurement precision. Besides, the electrical current can penetrate deeper into the subsurface before being dissipated. This allows more detailed information to be obtained about geological layers and subsurface characteristics at greater depths. For this reason, the geophysical campaign was carried out during the month of April, when climatic conditions are dry in Puerto Vallarta.

Hydrogeophysics provides efficient and non-invasive methods in subsurface data acquisition to identify subsurface rock heterogeneities and potential high-yield aquifer zones [19], and can be employed in salt intrusion studies. Results were anticipated that reflect a considerable decrease in the electrical resistivity of the subsoil, due to low resistivity anomalies. The presence of saline water is recognized as a good electrical conductor compared to fresh water, contributing to the reduction of resistivity. Furthermore, it was expected to observe characteristic manifestations in the resistivity profiles presented in the form of an arc. This phenomenon is attributed to the migration of saline water, which tends to form structures in the subsoil with arched contours. These expected results provided valuable information about the distribution and nature of salt intrusion in the studied area.

2.2 Data acquisition

Table 1. Physical Parameters of Electrical Resistivity Tomography (ERT1)

Layer	Thickness Meters	Resistivity Ω•m	Scale	Depth Meters
I	15	232.4-1000	High	15
II	5	72.3-173.6	Intermediate	20
III	20	7-54	Low	40

Electrode Setup: Current and potential electrodes were placed on the ground surface following the configuration.

Data Recording: Electrical current was applied through the electrodes, and potential readings were recorded at each measurement point (Table 1 and Table 2).

Table 2. Physical parameters of electrical resistivity tomography (ERT2)

Layer	Thickness Meters	Resistivity Ω•m	Scale	Depth Meters
I	1.5	54	Low	1.5
II	2	72.3 - 173.6	Intermediate	3.5
III	6.5	232.4 - 1000	High	10

2.3 Data processing

The data processing phase was crucial to ensure the quality and accuracy of the results obtained. Careful correction and processing of the raw data was carried out, aimed at eliminating noise and correcting possible systematic errors.

Subsequently, an iterative inversion process was implemented using the specialized tool Res2Dinv [20]. This method, based on finite elements, involves segmenting the model into smaller fragments, considering the conductivity in each one. In this context, a careful selection of the iteration was chosen that demonstrated a Root Mean Square Error (RMS) between 2% and 5%. This criterion guaranteed the robustness and precision of the results obtained.

The results of this iterative inversion process were exported in XYZ format, which facilitated graphical visualization of the generated models. These models were plotted and adjusted in an R programming environment, thus ensuring an accurate and detailed visual representation of the distribution of electrical resistivity in the subsurface.

3. RESULTS AND DISCUSSION

The resulting resistivity model was analyzed to identify anomalies that may indicate the presence of saline water (low electrical resistivity) in the subsurface.

3.1 Interpretation

The resistivity distributions are depicted in three main ranges: Low Resistivities (7-54 Ω•m); Intermediate Resistivities (72.3-173.6 Ω•m), and High Resistivities (311.1-1000 Ω•m). The 2D ERT images in the corresponding sections are described in detail below.

ERT1 is located parallel to the Pitillal River with an East-West (E-W) orientation. The resistivity in this area exhibits a complex structure composed of three different geoelectric layers.

The first layer presents high resistivities, fluctuating between 232.4 and 1000 Ω•m, with a uniform thickness of 15 meters in the range of 0 to 110 meters of horizontal distance. From 110 to 130 meters, a 20 meters wide resistive anomaly is detected, visualized in brown and orange tones in the graphic representations. This anomaly extends to a depth of 40 meters. The second layer is characterized by intermediate resistivities, varying between 72.3 and 173.6 Ω•m, with an approximate thickness of 5 meters.

The third and final layer reveals two low resistivity anomalies, with values between 7 and 54 Ω•m. The first anomaly is located at 140 and 150 meters (horizontal) and is associated with an artificial water reservoir in the subsoil. The second anomaly, the most prominent and intriguing, extends between 60 and 110 meters (horizontal) from a depth of 14 meters (Figure 4).

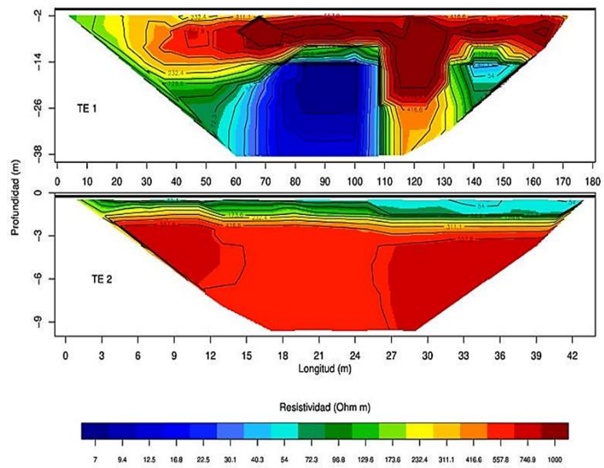

Figure 4. Image 2D ERT1 y ERT2

The low resistivity anomaly in this last layer is attributed to loose unconsolidated materials, such as water-saturated sands. It is crucial to note that the resistivity of groundwater varies in a range of 10 to 100 Ω · m, depending on the concentration of dissolved salts [21]. This finding provides valuable information on the nature and hydrogeological characteristics of the studied region, especially with regard to the presence of artificial deposits and the distribution of loose materials in the subsoil.

ERT2 runs perpendicular to ERT1 in a N-S direction. The first geoelectric layer presents low resistivities of 54 Ω•m with a thickness of less than 2 meters, and the second layer has intermediate values ranging from 72.3 Ω•m to 173.6 Ω•m with an estimated thickness of 2 meters. Consequently, below 3 meters, there is a 7 meters thick layer with resistivities ranging from 232.4 Ω•m to a maximum of 1000 Ω•m. No anomalies were found for ERT2.

3.2 Field verification

A field verification was conducted to confirm the interpretations through groundwater sampling to measure chloride levels and compare them with the model predictions.

Table 3. In-situ water quality assessment

Well	Permissible Limit Dissolved Chlorides WHO/NOM mg/L	Depth Meters	Resistivity Ω•m	Dissolved Chlorides Found mg/L
8	250	14	7	301

To validate the ERT results, a direct sampling was performed at Well No. 8 o determine its dissolved chloride content. Using a digital water quality meter, in-situ measurements were taken to determine the dissolved solids in mg/L, resulting in the following values in Table 3.

These results exceed the World Health Organization's (WHO) recommended limit of 250 mg/L. Contamination of drinking water with high salinity levels due to saline intrusion can have adverse effects on the health of individuals who consume this water. To achieve a quality of 250 mg/L, the average resistivity is 12.5 Ω•m.

The average resistivity, established as a target, is based on quality standards for the desired concentration of chlorides in the water. However, the actual measurement in the area identified with elevated chloride levels reveals a resistivity below expectation, indicating greater electrical conductivity in that specific area.

This discrepancy raises valuable questions about the local hydrogeology, highlighting the need for additional investigations to fully understand the relationship between electrical resistivity and chloride levels in the study area.

4. CONCLUSIONS

In a tourist destination like Puerto Vallarta, the supply of potable water is a fundamental resource for safeguarding the health and safety of both visitors and local residents, while also contributing to maintaining hygiene, cleanliness in the area, and facilitating tourist activities.

Potable water is a valuable and limited resource, making it crucial for tourist destinations to take measures to ensure its responsible and sustainable use. Tourists require access to safe and reliable drinking water for their well-being, but it is also essential to consider the availability of water for the local population, as well as the preservation of natural resources and biodiversity in the region.

If the demand for potable water continues to increase, and water is managed in the current manner, it is possible that underground supply sources may become depleted, potentially leading to a situation of water stress with negative recharge levels and the risk of contamination through saline intrusion.

Key Findings. The presence of chlorides, as detected through hydrogeophysical resistivity studies, in Well No. 8 in Puerto Vallarta, near the coast, may be attributed to the infiltration of saline water from the sea through its aquifer, likely caused by excessive groundwater extraction. This conclusion is grounded in the relationship between the electrical resistivity of groundwater. Saline water, containing ions such as chloride, is a better electrical conductor than freshwater. Therefore, when low electrical resistivity is observed in the ERT, it is indicative of the presence of saline water in the subsurface.

Importance and Relevance. Currently, the drinking water operator SEAPAL is carrying out actions to ensure the recharge of the aquifers through continuous measurement of the dynamic water levels in the extraction wells, thereby avoiding excess extraction. Trying to maintain optimal groundwater levels to ensure its sustainable use. In addition, for physical efficiency, which is the relationship between the water extracted and water losses (leaks in conduction lines, tanks, distribution network, household intakes, etc.) before reaching the consumer, according to the Indicator Program of Management of Operating Organizations (PIGOO) of the Mexican Institute of Water Technology (IMTA), SEAPAL maintains a physical efficiency (67.4%) above the national average (57.0%) [22] and continues working on improving the infrastructure hydraulic to make water distribution more efficient, without having to over-extract extra water. It is essential to maintain optimal levels of groundwater to ensure its sustainable use, since the border with the sea increases the risk of saline intrusion, contaminating the sources of water collection and extraction, which would worsen the future scenario. To comprehensively solve the problem of drinking water supply in Puerto Vallarta, it is necessary to increase, improve and make the hydraulic infrastructure more efficient.

It is essential to explore other sources of supply, given that current sources are insufficient to meet future demand. However, the most important measure is to make rational use of this vital liquid and promote a culture of responsible water use, promoting responsible practices to both tourists and locals to mitigate the risk of aquifer depletion and saline intrusion in tourist destinations such as Puerto Vallarta. This could be achieved by developing awareness campaigns aimed at tourists and residents to educate about the importance of water conservation and the risks associated with its misuse, using posters, brochures and digital media to disseminate clear messages and specific actions. Encourage the implementation of water-efficient technologies in hotels and resorts, such as water recycling systems, low-flow faucets and showers, and towel and linen reuse programs. Include information on water-saving practices when welcoming tourists, highlighting the importance of reducing shower time, turning off taps when not in use, and reusing towels and sheets when possible. Integrate educational programs into local schools and communities to teach children and residents about sustainable water management and the importance of preserving water resources. Promote the installation of infrastructure for collecting rainwater in public and private buildings, providing an additional source of water for non-potable uses. Support reforestation and conservation initiatives for watersheds such as the Pitillal River, to protect water sources and have greater collection of rainwater and recharge of aquifers. Implement recycling programs for treated wastewater for non-potable uses, such as irrigation of public green areas, thus reducing the demand for potable water for non-critical purposes. Establish monitoring systems to evaluate water use and apply management measures in real time. This may include detecting leaks and efficiently managing supplies during times of high demand. Foster collaboration between local government, the tourism industry, residents and community organizations to develop comprehensive water management strategies to jointly address challenges. These best practices would not only contribute to the mitigation of water risks, but would also foster a culture of responsible water use to ensure the long-term sustainability of the region.

Limitations of the Study. It is important to note that this conclusion is based on information provided by ERT and supported by additional analysis, such as direct water sampling to measure chloride levels and confirm water quality in the well.

It is important to note that the connection between the low resistivity findings of the ERT study and the presence of chlorides in Well No. 8 cannot be generalized throughout the area, because the data is limited, since at the date of the investigation, the resistivity data and the presence of water with high levels of chlorides have been obtained mainly from Well No. 8.

As the first study of this type and with the results obtained, it is imperative to continue with the investigations that include sampling of the other extraction sources located along the

Pitillal River basin, close to Well No. 8 and the ocean, in order to determine the consistency of the correlation across different locations. With the inclusion of data from multiple wells, it would allow a more complete and robust evaluation to validate and extend the results and inform the competent authorities for the necessary actions.

Future Research Directions. To address these challenges, further hydrogeophysical studies are necessary to determine the static and dynamic levels of different groundwater extraction wells, allowing operators of drinking water to establish maximum extraction levels to reduce overexploitation and prevent saline intrusion. Reducing groundwater extraction can help maintain freshwater pressure in the aquifers. Additional tests are needed to better understand the extent and distribution of this saline water in the aquifer. Results should be compared with well locations and the chloride levels recorded in them.

The specific hydrogeophysical studies that could be most beneficial would be: Vertical Electrical Soundings, continuing with resistivity tomography in multiple wells in the area, allowing a more detailed characterization of the variations in the electrical properties of the subsoil at different depths, identifying possible aquifer layers and areas of saline intrusion. Three-Dimensional Resistivity Mapping: Make a three-dimensional resistivity map in the study area, to provide a detailed spatial representation of the distribution of resistivity in the subsoil, allowing a better understanding of the extent and connectivity of the aquifer formations. Continuous Resistivity Monitoring: Establish continuous resistivity monitoring stations to obtain data over time. Essential to detect changes in the rainy or dry season, especially in response to climatic variations or changes in land use. Analysis of Electrical Conductivity of Water: Complement resistive studies with analysis of the electrical conductivity of water in samples extracted from wells. This would provide direct information on groundwater salinity and allow results to be correlated with resistivity measurements. Integration with Geological Data: Integrate hydrogeophysical data with detailed geological information, allowing a more precise interpretation of how the geological characteristics of the study area could influence the distribution of resistivity and salt intrusion.

Improving water resource management can contribute to ensuring a sustainable supply of drinking water.

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NOMENCLATURE

Ω•m	Specific electrical resistivity of a material
ERT	Electrical Resistivity Tomography
SEAPAL	System of Drinking Water, Drainage, and Sewerage Services of Puerto Vallarta
Mg/L	Milligrams per liter