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Geoelectrical Characterization as a Criterion for the Implementation of a Riverbank Filtration System in the Roldanillo–Unión–Toro (RUT) Agricultural Irrigation District, Colombia

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Abstract

Increasing pressure on surface water resources in intensive agricultural regions has driven the search for sustainable alternatives for irrigation supply, especially in areas where water quality limits crop safety and export opportunities. In this context, riverbank filtration (RBF) systems offer a nature-based solution by utilizing physical, chemical, and biological processes associated with river–aquifer exchange. However, their implementation depends on suitable site selection supported by hydrogeological, geomorphological, and hydraulic criteria. This study developed an integrated methodology to identify zones with potential for implementing RBF systems in the Roldanillo–Unión–Toro irrigation district, located in northern Valle del Cauca, Colombia. This region requires irrigation water over 10,256 ha of agricultural land (mainly sugarcane, maize, grapes, and guava). We combined geophysical methods (vertical electrical soundings, 2D electrical resistivity tomography, and passive seismic), geotechnical methods (CPTu tests), and hydraulic characterization of the river reach to evaluate subsurface stratigraphy, preliminary hydrogeological suitability, inferred river–aquifer connectivity conditions, and channel stability. The evaluation covered four sectors along an approximately 21 km stretch of the Cauca River's left-bank alluvial valley. The results revealed pronounced lateral and vertical heterogeneity of alluvial materials. However, the "El Palmar" sector was identified as the best-supported priority sector for future RBF validation, due to the presence of profile-scale evidence of potentially permeable sandy and gravelly units with intermediate resistivity values (52–61 Ω·m), favorable stratigraphic organization, and stable river-reach conditions during the field campaign. In contrast, the other three sectors (La Esperanza, Candelaria, and Cayetana) showed more fine-grained sediments with deeper permeable strata. River-flow measurements during the July 2025 field campaign indicated high discharge conditions at the evaluated reach, while river-channel observations showed active fine-sediment transport; these findings provide hydraulic and sedimentary context for the future evaluation of induced infiltration and potential clogging, but do not constitute direct evidence of river–aquifer exchange. This study highlights the value of integrated screening approaches for prioritizing candidate RBF sites in agricultural alluvial settings, while indicating that pumping tests, piezometric monitoring, hydraulic-gradient analysis, and water-quality validation remain necessary before engineering implementation.

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1. Introduction

Increasing pressure on surface-water resources, driven by rising agricultural demand, climate variability, and progressive deterioration of raw-water quality, has intensified the search for sustainable and operationally reliable water-supply alternatives in highly productive agricultural regions [1]. In this context, riverbank filtration (RBF) has emerged as an efficient and robust abstraction strategy because it takes advantage of the natural physical, chemical, and biological filtration processes that occur during induced infiltration from the river channel into alluvial sediments and the adjacent aquifer [2]. The effectiveness of RBF systems depends on the degree of river–aquifer interaction, riverbed hydraulic conductivity, the geometry and continuity of alluvial deposits, and the hydraulic and sedimentary stability of the river channel [3]. In practical terms, this means that RBF performance is governed not only by the existence of a permeable aquifer, but by the entire hydrogeomorphic setting that controls induced recharge, residence time, and the preservation of infiltration capacity over time.

Although RBF has been widely studied and applied for drinking-water pretreatment, its use for agricultural irrigation remains comparatively less developed, particularly in tropical environments where high suspended-sediment loads, pathogen contamination, strong seasonal variability, and fluctuating river quality may compromise the performance of pressurized irrigation systems. Under these conditions, the value of RBF extends beyond simple water abstraction. It also lies in its ability to stabilize raw-water quality, reduce solids and microbial loads, and improve the operational reliability of irrigation systems that are highly sensitive to the clogging of emitters and water-quality fluctuations [4]. This issue is especially relevant in horticultural production, where irrigation-water quality directly affects infrastructure protection, product quality, and compliance with the phytosanitary standards required for market access.

The correct siting of RBF systems therefore becomes a central technical challenge, especially in heterogeneous alluvial environments. Recent methodological work has shown that successful site selection depends on the combined assessment of hydraulic connectivity between the river and the aquifer, aquifer transmissivity, river geometry, clogging potential, and both surface-water and groundwater quality, rather than on any single hydrogeological variable considered in isolation [5,6]. In the present study, hydraulic connectivity is therefore treated as a site-selection criterion inferred from the geometry, continuity, depth, and texture of alluvial units and their relationship with river-reach conditions, rather than as a directly measured hydraulic response based on piezometric gradients, pumping tests, or tracer experiments. In this regard, geophysical methods, and particularly geoelectrical techniques, are highly valuable because they provide indirect but spatially distributed information on the thickness of alluvial deposits, the location of permeable units, and the occurrence of fine-grained materials that may restrict induced infiltration. Likewise, previous field applications have shown that the combined use of vertical electrical sounding (VES), electrical resistivity tomography (ERT), and hydrochemical information can effectively delineate river–aquifer interaction zones and support the identification of viable RBF well locations under complex hydrogeological conditions [7].

A further difficulty in tropical alluvial systems is that favorable hydraulic conditions cannot be inferred from lithology alone. Even where sands and gravels are present, infiltration performance may still be limited by vertical and lateral facies changes, shallow

fine-grained layers, riverbed clogging, or unstable channel conditions [8,9]. These controls may alter residence times, hydraulic gradients, and the effective contribution of induced bank filtrate to pumped water, thereby affecting both system productivity and water-quality improvement [10–12]. Consequently, RBF site selection requires an integrated framework capable of linking subsurface structure, geotechnical behavior, channel hydraulics, and near-channel sediment conditions that may influence infiltration and clogging. From this perspective, multiscale characterization is not only useful for describing the physical setting, but also for reducing uncertainty in the hydrogeological interpretation before moving toward pilot-scale implementation and engineering design [13,14].

Despite the increasing international interest in RBF, field-based studies that evaluate site suitability in tropical alluvial systems remain comparatively limited, particularly for agricultural irrigation and for Colombian or Latin American river corridors. Much of the available literature has focused on drinking-water applications, conceptual design, or temperate-region case studies, whereas empirical assessments combining geophysical, geotechnical, and river-reach information for irrigation-oriented RBF planning are still scarce. This gap provides the scientific rationale for evaluating the RUT district as a tropical agricultural case study where RBF feasibility must be interpreted from multiple, complementary lines of field evidence.

In northern Valle del Cauca, Colombia, an extensive agricultural area depends on efficient, continuous, and reliable water management, as exemplified by the Roldanillo–Unión–Toro irrigation district (RUT). In this setting, the increasing need for irrigation water of sufficient quality to support crops that comply with phytosanitary and commercial requirements, together with the limitations imposed by current river-water quality, has created the need to identify alternative and complementary water sources associated with the alluvial deposits of the Cauca River valley [15]. Locating sectors with hydrogeological potential for RBF therefore represents a relevant strategy for improving long-term access to irrigation water of more stable quality, while also supporting the transition toward higher-value and more water-sensitive production systems.

The novelty of this study lies in applying an integrated geophysical–geotechnical–hydraulic site-selection framework to evaluate RBF feasibility for agricultural irrigation in a tropical alluvial setting, where RBF has been much less explored than in drinking-water applications. Rather than assessing RBF potential from geoelectrical information alone, the study combines sector-scale VES screening, local ERT imaging, CPTu-based hydrostratigraphic confirmation, passive seismic characterization, and river-reach hydraulic observations to support a technically defensible prioritization of the most favorable implementation sector.

In this study, geoelectrical, geotechnical, and hydraulic information were integrated, including VES, ERT, CPTu testing, passive seismic measurements, and interpretation of the alluvial sequence and river reach conditions, in order to characterize the subsurface condition and the local river–aquifer setting within the RUT district. This multiscale approach allowed the geometry of the alluvial medium, its mechanical properties, and the capacity of the river–aquifer system to be evaluated jointly. The overall objective of the study was to identify and technically justify the most favorable sector for future RBF implementation in the RUT district through an integrated site-selection framework. The working hypothesis was that the most suitable sector for future RBF implementation would not necessarily correspond to the sector with the highest resistivity values or the coarsest inferred materials, but to the sector where independent lines of evidence converge: permeable alluvial units at manageable depth, lateral continuity of the target horizon, shallow fine-textured layers capable of contributing to natural filtration without fully

restricting infiltration, stable river-reach hydraulic conditions, and mechanically compatible alluvial sediments.

2. Methodology

2.1. Study Area Description

The study was conducted in the RUT district located on the western bank of the Cauca River in the northern part of Valle del Cauca Department, Colombia (Figure 1). Four analysis sites were defined along an approximately 21 km river corridor: El Palmar (4.403056° N, 76.105033° W), La Esperanza (4.444158° N, 76.077403° W), Candelaria (4.480264° N, 76.080044° W), and Cayetana (4.579805° N, 76.040323° W) (Figure 1).

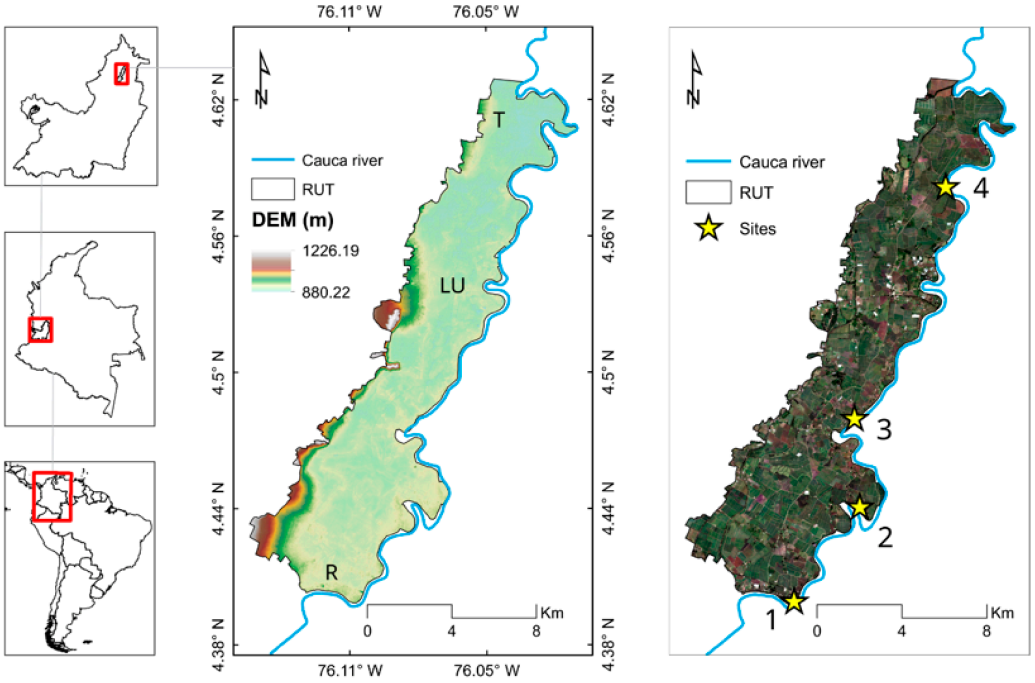


Figure 1. Location of the RUT district. Left: inset maps, from bottom to top: South America, Colombia, Valle del Cauca. Center: Digital elevation model (DEM) and municipalities (R: Municipality of Roldanillo, LU: Municipality of La Unión, and T: Municipality of Toro). Right: RGB map and sampling sites represented by a yellow star (sampling site 1: El Palmar, sampling site 2: La Esperanza, sampling site 3: Candelaria, and sampling site 4: Cayetana).

The RUT district, located in Valle del Cauca, covers 10,256 ha distributed across three municipalities (Roldanillo, La Unión, and Toro) and lies at an elevation of approximately 930 m above sea level on the alluvial plain of the left bank of the Cauca River, near the Western Cordillera. The region is characterized by broad alluvial plains and the alluvial aquifer of the Cauca River valley. The climate is moderately warm tropical, with a mean annual temperature of 24 °C and a bimodal precipitation regime averaging 1015 mm per year. The terrain has gentle slopes, with elevations ranging from 950 to 1050 m [16].

The dominant land use within the RUT district is sugarcane, which occupies 5407.88 ha. Other relevant crops include maize (2180.36 ha), grapevine (501.15 ha), and guava (454.71 ha). The district integrates large-scale agriculture with smallholder-managed horticultural production. It currently comprises approximately 1611 agricultural fields smaller than 10 hectares, 255 fields ranging from 10 to 50 hectares, and 16 fields between 50 and 100 hectares in size [16]. Annual irrigation demand is estimated at approximately 59.1 million m^3, supplied through two intake structures on the Cauca River and an unlined canal network [4,15].

Despite its strong agricultural potential, the RUT district faces important water-quality constraints that may affect product quality and limit export opportunities. At the Cauca River intake supplying the district, suspended solids ranged from <20 to 558 mg/L, organic matter ranged from 2.53 to <10 mg O_2/L for biochemical oxygen demand and from <10 to 41.50 mg O_2/L for chemical oxygen demand, nutrients ranged from 0.64 to 1.65 mg $N–NO_3$/L for nitrate and from <0.100 to 4.14 mg PO_4/L for phosphate, and pathogen indicators ranged from 1.7×10^3 to 9.6×10^6 MPN/100 mL for total coliforms and from 240 to 23,500 MPN/100 mL for fecal coliforms [4]. These conditions reduce the efficiency and service life of pressurized irrigation systems and increase the food-safety risks for high-value horticultural crops. These values were used only to contextualize the water-quality constraints affecting the RUT district and were obtained from previously reported monitoring information at the Cauca River intake. Therefore, they should be interpreted as background evidence of water-quality variability rather than as a new water-quality dataset generated by this study. The present field campaign did not include repeated water-quality sampling, statistical time-series analysis, or estimation of seasonal water-quality descriptors.

The marked variability in water quality highlights the need for pretreatment strategies capable of providing irrigation water of adequate quality. These limitations, together with the low drainage capacity reported in some areas of the district (23.5%), increase the demand for chemically stable water to protect infrastructure, safeguard public health, and facilitate the transition toward higher-value production systems [17,18].

The study was developed through an integrated methodology that included compilation and analysis of secondary information, acquisition of geophysical field data, comparative geoelectrical interpretation across four sectors, and investigation of the most favorable sector through CPTu, passive seismic, and river-reach hydraulic characterization (Figure 2).

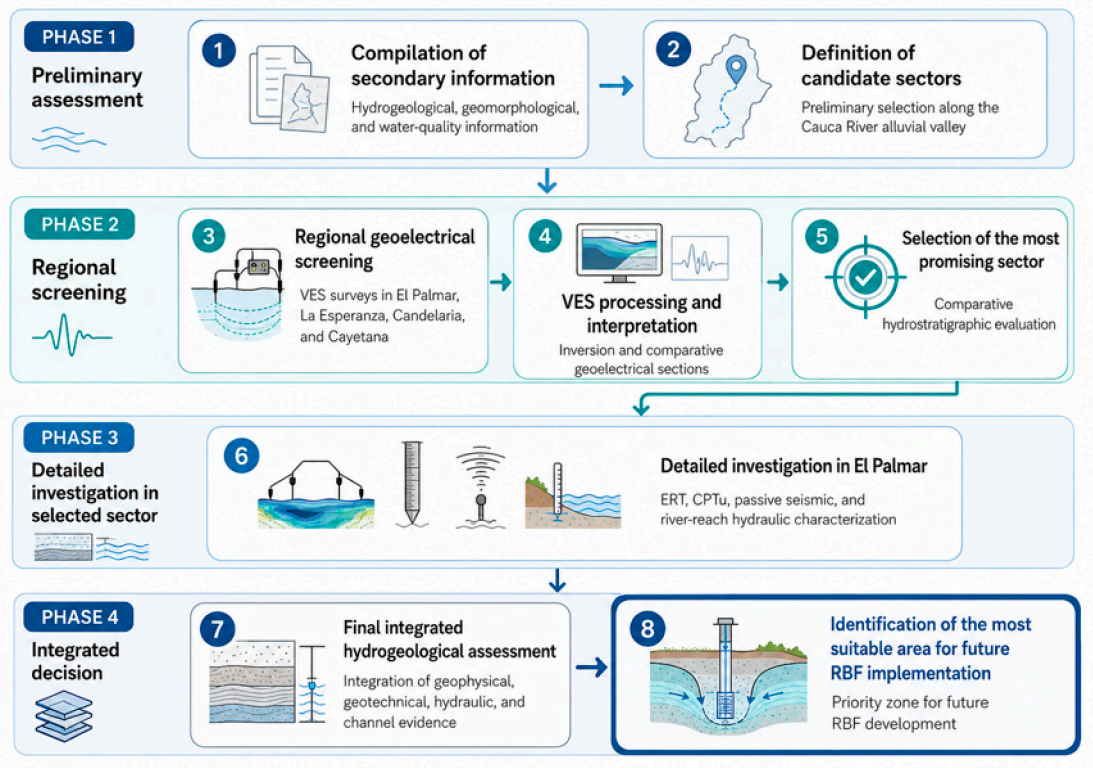


Figure 2. Workflow of the integrated methodology used to identify the most suitable sector for future RBF implementation in the RUT district. This figure was created using ChatGPT version 5.5 (https://openai.com/).

2.2. Geoelectrical Exploration

Ten VES surveys were conducted in the El Palmar, La Esperanza, Candelaria, and Cayetana sectors (Figure 3) using a Terrameter ABEM SAS-300C with a Schlumberger array (ABEM Instrument AB, Bromma, Sweden), considered potentially suitable for locating an RBF system, in order to compare subsurface composition and its potential for groundwater storage and transmission. Based on the results obtained, one geoelectrical section was constructed for each sector, representing the spatial distribution, thickness, and depth of the main subsurface units through correlation of the resistivity values derived from the inverted layered models. Investigation depth was progressively increased by expanding the spacing between the current electrodes, whereas the electrical response of the subsurface was recorded through the potential electrodes. This geoelectrical prospecting method is useful for distinguishing permeable materials such as saturated gravels and sands from less conductive or more compact media such as silts and clays, thereby delimiting the zones most suitable for water abstraction and the efficient operation of RBF systems [19,20]. The maximum VES investigation depth was 100 m. The number of VES measurements was defined according to the screening purpose of the study and the logistical constraints associated with field geophysical work along the Cauca River corridor. The survey was not intended to generate a continuous hydrogeological model of the entire 21 km reach, but to compare four preselected sectors with potential relevance for RBF implementation. Therefore, the VES points were used as sector-level exploratory controls to identify broad contrasts in the depth and continuity of units interpreted as potentially permeable alluvial materials. Given the known lateral variability of alluvial systems, the resulting geoelectrical sections should be interpreted as preliminary screening tools rather than as exhaustive representations of subsurface heterogeneity across the full river corridor.

At El Palmar (Figure 3a), because of its high hydrogeological potential, lateral heterogeneities were further examined by means of two-dimensional ERT using a Wenner–Schlumberger array and the same Terrameter ABEM SAS 300-C unit (ABEM Instrument AB, Bromma, Sweden). The ERT profile was 168 m long, with an investigation depth of approximately 31 to 33 m, using 22 electrodes spaced 8 m apart. This profile was considered representative of the local candidate reach at El Palmar because it was positioned within the sector prioritized by the VES screening, across a relatively uniform alluvial surface with no marked topographic discontinuities, and under field conditions considered suitable for evaluating the lateral continuity of the near-river alluvial sequence; nevertheless, it was not intended to represent the full lateral heterogeneity of the entire El Palmar sector. ERT makes it possible to obtain two-dimensional or three-dimensional images of the spatial distribution of resistivity, thereby revealing the actual geometry of the aquifer, its lateral continuity, the effective thickness of permeable units, and the presence of structural or lithological discontinuities that cannot be identified from isolated VES measurements [21,22].

After the initial VES-based screening, the four sectors were not investigated with the same level of detail because the purpose of the first stage was to identify the sector with the highest potential for future RBF implementation. This unequal sampling intensity was an intentional consequence of the phased screening design. The first stage was used to identify whether each sector presented minimum hydrostratigraphic conditions compatible with practical RBF implementation, especially the presence of potentially permeable units at manageable depth and with sufficient continuity. Detailed characterization was then concentrated on the sector that satisfied these preliminary conditions most clearly. This approach reduced unnecessary field effort in sectors where the VES interpretation indicated less favorable configurations, but it also means that the comparison among sectors should be understood as a screening-level prioritization rather than as a fully equivalent, site-by-site engineering design assessment. La Esperanza and Cayetana were evaluated through

the same VES procedure used in the comparative screening stage, and their inverted layered models were correlated to construct the corresponding geoelectrical sections. These sections were used to assess the depth, thickness, and continuity of the main subsurface units and to compare their preliminary hydrostratigraphic suitability with that of El Palmar and Candelaria. No additional ERT, CPTu, passive seismic, or detailed river-reach characterization was conducted in La Esperanza or Cayetana because the preliminary geoelectrical interpretation indicated less favorable conditions for RBF siting, mainly associated with fine-grained shallow materials and permeable units located at greater depths.



Figure 3. Location of VES points. (**a**) El Palmar (sampling site 1); (**b**) La Esperanza (sampling site 2); (**c**) Candelaria (sampling site 3); (**d**) Cayetana (sampling site 4).

In the Candelaria sector, only one VES was performed (Figure 3c) because the recorded profile showed low resistivity values over the investigated interval, which were interpreted as predominantly clayey and silty materials under the local geological context. This result did not provide preliminary evidence of shallow or intermediate permeable units comparable to those identified in El Palmar. Therefore, Candelaria was not prioritized for second-stage investigation within the resource- and time-constrained screening design. This decision should not be interpreted as a definitive exclusion of the entire Candelaria sector, because additional VES, ERT, borehole, or hydraulic data would be required to characterize its full lateral heterogeneity. Based on the comparative interpretation of the VES data from the four sectors, El Palmar was identified as the most favorable sector for additional

investigation. Consequently, this sector was selected for detailed characterization, including ERT, CPTu tests, streamflow measurements, and passive seismic surveys, in order to refine the conceptual subsurface model and assess the local conditions relevant to future RBF implementation.

The integration of the methodological stages followed a sequential screening logic rather than a formal weighted multicriteria model. In the first stage, the four sectors were compared using VES-derived geoelectrical sections to identify the depth, thickness, and continuity of units interpreted as potentially permeable alluvial materials. Sectors were considered less favorable when shallow and intermediate depths were dominated by clayey or silty materials or when the units interpreted as sands and gravels occurred only at depths considered less practical for RBF implementation. In the second stage, the sector with the most favorable preliminary hydrostratigraphic configuration was evaluated in greater detail using ERT to verify lateral continuity and geometry, CPTu to support stratigraphic and geotechnical interpretation, passive seismic data to assess mechanical consistency of the alluvial sequence, and river-reach hydraulic observations to contextualize the feasibility of induced infiltration and potential sediment-related constraints. No numerical weights were assigned to the criteria because the objective was not to rank the sectors through a calibrated decision model, but to identify whether the available independent lines of evidence converged toward a technically defensible priority sector for future pilot-scale validation.

2.3. Data Processing

The apparent resistivity data were processed using REXIS PLUS v.3 (IX1D), which applies a direct inversion algorithm based on EAEG master curves to estimate the true resistivity and thickness of each geoelectrical unit. In El Palmar, identified as the area with the highest hydrogeological potential, the electrical tomography dataset was processed using RES2DINV (Seequent, Christchurch, New Zealand), which provided improved resolution of lateral heterogeneities and aquifer-body geometry. The available project records did not include a complete report of inversion-quality metrics such as RMS error, convergence thresholds, model sensitivity, or alternative inversion runs. Therefore, the geoelectrical models were interpreted as screening-level hydrostratigraphic evidence rather than as uniquely constrained quantitative subsurface models. To reduce interpretive uncertainty, the resistivity results were evaluated in relation to local geomorphological context, expected alluvial lithofacies, CPTu-based stratigraphic classification, passive seismic evidence, and river-reach hydraulic observations. Because VES inversion is inherently non-unique and its vertical resolution decreases with depth, interpretations of deeper layers were treated with greater caution than shallow and intermediate intervals. Therefore, layers interpreted at depths close to or greater than the maximum effective investigation range were used mainly to identify broad hydrostratigraphic tendencies, whereas site prioritization emphasized the relative depth, continuity, and accessibility of potentially permeable units rather than precise deep-layer thickness estimates.

Additional field observations from the selected river reach were incorporated into the integrated interpretation of site suitability. These observations included streamflow-related hydraulic measurements and channel-condition information used to contextualize the feasibility of induced infiltration and potential sediment-related constraints. One CPTu sounding, identified as CPTu-DR-01, was conducted in the El Palmar sector and processed using CPeT-IT v.3.3.2.17. The term "profiles" refers to the normalized CPTu parameter profiles derived from this sounding, including Qtn, Fr, Bq, Ic, and the SBTn-based soil behavior type classification, rather than to multiple CPTu test locations. The passive seismic records from line MAM-1 were processed using Geopsy (SESAME European Project, Granoble, France) and SPAC-RT (Subsuelo3D, Bogotá, Colombia) to obtain the

phase velocity–frequency dispersion image and the corresponding inverted 1D shear-wave velocity (Vs) model.

2.4. Geoelectrical Criteria for RBF Site Selection

Electrical resistivity of the subsurface provides an indirect means of inferring the hydraulic behavior of earth materials. However, because the relationship between resistivity and permeability is not linear and depends on multiple lithological and hydrodynamic factors, including grain size, porosity, and degree of saturation [23], it was necessary to integrate the lithological and geomorphological context in order to identify the permeable materials in each sector more reliably.

In alluvial systems, soils composed of saturated gravels and sands typically show resistivity ranges associated with high hydraulic conductivity and good river–aquifer connectivity, whereas fine-grained materials such as silts and clays exhibit lower resistivities linked to low permeability and high water retention [19,24].

The siting and design of wells for RBF systems must be based on an adequate hydrogeological characterization of the alluvial aquifer. Aquifers with hydraulic permeabilities on the order of 10^{-3} to 10^{-4} m/s are generally considered favorable because they allow efficient water transfer through the porous medium [4]. Likewise, hydraulic connectivity between the river channel and the aquifer is a fundamental criterion because the operating principle of RBF is based on the induction of lateral flow from the river [25]. In addition, sectors with a saturated thickness usually greater than 6 m in alluvial aquifers are prioritized in order to ensure effective storage volume and stable system operation [26].

From a spatial standpoint, the lateral distance between the well and the river channel is a critical parameter because it controls the groundwater residence time, and therefore the effectiveness of natural treatment by filtration, with optimal ranges commonly reported between approximately 20 and 120 m depending on aquifer permeability, river morphology, and local hydrodynamic conditions [4]. Successful systems are often located 15 to 100 m from the river in order to balance water quality, hydraulic efficiency, and construction cost [27,28]. Likewise, well depth must be selected to optimize the balance between induced infiltration from the river and abstraction of native groundwater; in agricultural settings, typical depths range from 9 to 50 m [29,30].

Within this broader hydrogeological and design context, geoelectrical information provides an additional line of evidence for interpreting the subsurface conditions that may favor or restrict groundwater abstraction through vertical wells. However, because resistivity ranges commonly overlap among different alluvial materials, the interpretation of texture or predominant lithology was not based on resistivity values alone. Instead, the resistivity intervals were interpreted using local expert geological knowledge, the geomorphological setting of the Cauca River alluvial plain, and the expected hydrostratigraphic behavior of sands, gravels, silts, and clays under saturated conditions. Accordingly, Table 1 presents approximate literature-based reference ranges that supported, but did not replace, expert geological interpretation. The hydraulic-permeability values were revised to maintain consistency with the expected decrease in hydraulic conductivity from gravels and sands to silts and clays. These ranges should therefore be understood as an interpretive framework rather than as fixed diagnostic thresholds for material classification or RBF suitability. Because no borehole logs or direct lithological samples were available for all four sectors, the material assignments derived from VES were treated as hydrostratigraphic interpretations with variable confidence rather than as direct geological confirmation. Consequently, isolated resistivity intervals within a favorable range were not considered sufficient for site prioritization unless they were consistent with a practical

hydrostratigraphic configuration for RBF, including manageable depth, continuity, and favorable relationship with overlying materials.

Table 1. Approximate reference resistivity and hydraulic-permeability ranges used to support expert hydrogeological interpretation of potential subsurface units. The values are indicative and may overlap among sediment types depending on grain-size distribution, clay content, pore-water conductivity, saturation, compaction, and local depositional context.

Resistivity Range (Ω·m)	Potential Subsurface Unit	Hydraulic Permeability	Hydraulic Behavior	Study
300–1000	Fractured rock beneath alluvium	Variable (commonly fracture-controlled)	Fracture-controlled flow	[31–33]
100–500	Saturated gravels and coarse sands	High (10^{-2}–10^{-3} m/s)	High conductivity; rapid and stable flow	[33,34]
50–300	Medium sands	Moderate to high (10^{-3}–10^{-4} m/s)	Efficient flow with good river–aquifer connectivity	[24,33,35,36]
50–200	Fine sands	Moderate to low (10^{-4}–10^{-5} m/s)	Moderate flow; greater particle retention	[33,37,38]
10–100	Sandy silts	Low (10^{-5}–10^{-6} m/s)	Slow flow; transition between sand and silt	[33,37,39]
3–50	Silts	Low to very low (10^{-6}–10^{-8} m/s)	Low conductivity; high retention	[33,40]
1–50	Clays	Very low (<10^{-8} m/s)	Practically impermeable	[33,38,39,41]

3. Results

3.1. Geoelectrical Characterization

Geoelectrical surveying resolved marked differences in subsurface resistivity structure among the evaluated sectors, allowing a comparative, screening-level interpretation of their hydrostratigraphic suitability for RBF (Figure 4). In the study zone, the results suggest that fine-grained materials dominate the shallow subsurface in most sectors, although their thickness, continuity, and relationship with deeper units interpreted as more permeable vary substantially. Candelaria represented the least favorable preliminary screening result, as the available VES showed consistently low resistivity values (<30 Ω·m) over the investigated interval, which were interpreted as being consistent with predominantly clayey and silty strata and provided little evidence of shallow or intermediate units favorable for induced infiltration. Because this response did not reveal a hydrostratigraphic target comparable to El Palmar, the sector was not prioritized for second-stage characterization; however, this interpretation remains screening-level and does not rule out local heterogeneity beyond the single sounding location [42–44]. Thus, the Candelaria interpretation should be understood as a preliminary reduction in priority under the available screening evidence, not as final site elimination.

In contrast, El Palmar, La Esperanza, and Cayetana showed more internally differentiated resistivity architectures. In El Palmar (sampling site 1) (Figure 4a), the geoelectrical section suggests a comparatively thinner upper interval, approximately 25 m thick, interpreted as interbedded silts and sands and overlying deeper materials of greater hydrogeological interest. In La Esperanza (sampling site 2) (Figure 4b), the shallow section is interpreted as more uniformly fine-grained, with resistivity patterns consistent with silts and clays extending through the first ~35 m, followed by possible interbedded sandy-silty layers down to about 80 m and only then by units interpreted as sands and gravels at greater depth. Cayetana (sampling site 4) (Figure 4c) also exhibits a vertically heterogeneous arrangement, but with a shallow sequence broadly similar to that of El Palmar and La Esperanza is characterized by resistivity patterns consistent with the predominance of silts and clays within the upper ~25 m, and possible interbedded sandy-silty materials below.

Taken together, these results show that the sectors are not differentiated simply by the inferred presence or absence of coarse deposits, but by the interpreted depth, thickness, and continuity of fine-grained versus more permeable units, which are the most relevant features for preliminary RBF screening.

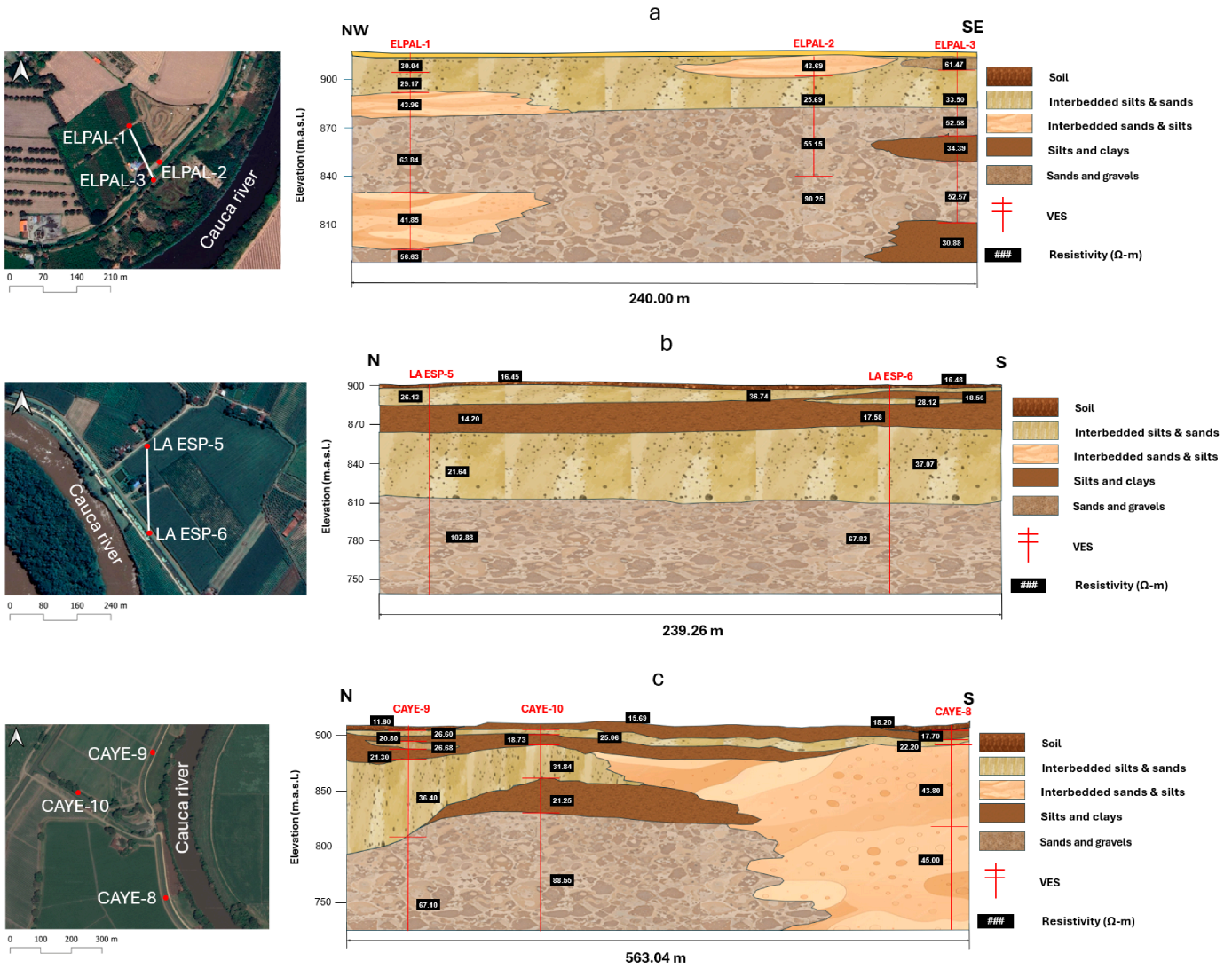


Figure 4. Geoelectrical sections of (**a**) the El Palmar sector (sampling site 1); (**b**) La Esperanza sector (sampling site 2); (**c**) Cayetana sector (sampling site 4). The three ### represent resistivity values.

3.2. Influence of Electrical Resistivity on Geological Units

Based on the interpretation of the electrical resistivity profiles (Figure 4) and the information summarized in Table 1, zones with resistivity values consistent with alluvial materials such as medium sands (50–300 Ω·m), coarse sands, and gravels (100–500 Ω·m) were identified. Because these ranges may overlap with other sediment types, the units were interpreted as potential permeable horizons only when the resistivity values were coherent with the local geomorphological context, the expected alluvial architecture, and their relative depth and continuity within each sector. These interpreted units were considered consistent with the expected balance between water saturation and hydraulic connectivity with the river channel, a condition regarded as essential for RBF systems [1,36,45]. Accordingly, the resistivity values associated with potential sands and gravels at each sector were compiled in Table 2 in order to identify the site with the greatest preliminary hydraulic potential for RBF system placement.

Table 2. Occurrence of units interpreted as potential sands and gravels at each sampling point in each sector based on the layered-model results and local hydrogeological interpretation. The listed resistivity values indicate intervals with potential hydrogeological interest, but site suitability was evaluated considering their depth, continuity, overlying materials, and practical relevance for RBF implementation, not resistivity magnitude alone.

Sector	Sampling Points	Resistivity (Ω·m)	Depth (m)
El Palmar	ELPAL-1	63.84	87.46
		56.63	>121.00
	ELPAL-2	55.15	80.45
		90.25	>80.00
	ELPAL-3	61.47	10.66
		52.58	50.98
		52.57	104.82
La Esperanza	LAESP-5	102.88	>90.00
	LAESP-6	67.82	>90.00
Candelaria	CANDE-7	103.80	>60.00
Cayetana	CAYE-9	67.10	>95.00
	CAYE-10	88.55	>80

From Table 2, the El Palmar profile ELPAL-3 was identified as having intermediate resistivity values (between 52 and 61 Ω·m) from approximately 10 to 100 m depth, which were interpreted cautiously as being consistent with potential saturated, relatively permeable alluvial materials under the local geomorphological context (Table 1). This interpretation should not be understood as a direct lithological or hydraulic-conductivity determination, because resistivity may also be influenced by pore-water chemistry, saturation conditions, clay content, and compaction. Although Candelaria showed one relatively high resistivity value (103.80 Ω·m) at a depth greater than 60 m, this value was not interpreted as sufficient evidence of RBF suitability because the available VES response indicated low-resistivity, fine-grained conditions over the shallower and intermediate intervals that are more relevant for practical riverbank filtration design. Therefore, the interpretation did not depend on the presence of an isolated resistivity value within the range of potential sands or gravels, but on the vertical position, continuity, and accessibility of the inferred permeable units. In contrast, La Esperanza, Candelaria, and Cayetana were characterized mainly by low-resistivity shallow and intermediate intervals, interpreted as clayey-silty and sandy-silty sections, while the intervals interpreted as potential sands or gravels occurred at depths or positions that were less favorable for practical RBF implementation.

Within El Palmar, ELPAL-3 should therefore be interpreted as the most favorable local hydrostratigraphic window identified during the VES screening, rather than as an isolated basis for sector selection; its relevance is supported by the broader El Palmar context, including the flat alluvial setting, absence of marked local topographic discontinuities, homogeneous climatic forcing across the sector, and the subsequent ERT, CPTu, and passive seismic evidence collected within the same candidate reach.

3.3. Depth of Alluvial Deposits and Uniformity of the Geoelectrical Sections

The most permeable layers, interpreted as potential sands and gravels, were also identified in La Esperanza, Candelaria, and Cayetana; however, they generally occurred at depths or positions less favorable for practical RBF implementation (Table 2). In comparison, El Palmar showed the most favorable combination of intermediate resistivity values, shallower occurrence of potentially permeable units, and greater practical accessibility. Although ELPAL-1, ELPAL-2, and ELPAL-3 showed internal variability, this variability was

interpreted as expected facies heterogeneity within the same flat alluvial setting rather than as evidence of unrelated hydrogeological compartments. Among these profiles, ELPAL-3 represented the clearest local expression of the target configuration, while the detailed ERT, CPTu, and passive seismic characterization provided additional support for the interpretation of El Palmar as the priority sector.

3.4. Characterization of the Sector with the Highest Hydrogeological Potential for the RBF System

After El Palmar was identified as the sector with the highest hydrogeological potential, lateral heterogeneities were further evaluated by means of electrical tomography. The survey had a length of 168 m and an analysis depth of 31.6 m, allowing for the interpretation of aquifer geometry, lateral continuity, and lithological variability (Figure 5).

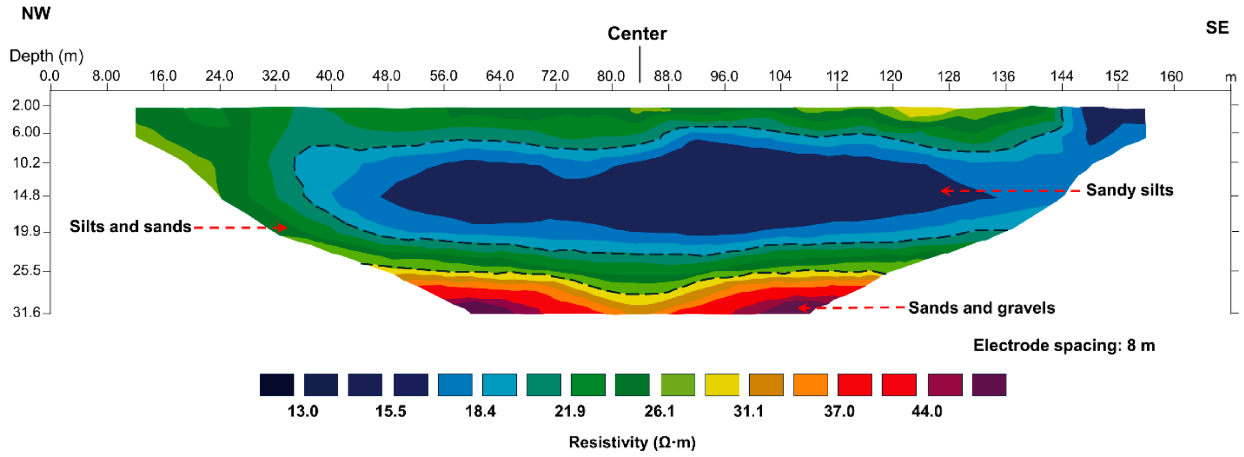


Figure 5. Electrical tomography of the El Palmar sector.

Figure 5 highlights two relevant resistivity domains along the 168 m ERT transect. The first is a low-resistivity transition layer (13–18.4 Ω·m) within the upper 25 m, interpreted as being consistent with sandy-silt strata under the local alluvial context. This domain was laterally traceable over approximately 120 m of the profile, which was used as the main geometric indicator of continuity along the selected transect. The second is a deeper, comparatively higher-resistivity unit (>30 Ω·m), interpreted as a potential sand-and-gravel-bearing alluvial body. This lower domain was considered geometrically coherent where it appeared as a continuous resistivity body within the ERT image; however, its continuity should be understood as profile-scale continuity along the investigated transect, not as sector-wide continuity across the entire El Palmar area.

3.5. Confirmation of the Stratigraphic Model and Hydrogeological Control

Integration of the electrical tomography with the CPTu-DR-01 sounding provided local geotechnical support for interpreting a stratified alluvial sequence in the El Palmar candidate reach, dominated by fine sediments in the shallow section and more permeable materials at depth. The normalized CPTu parameter profiles from this sounding showed a heterogeneous vertical sequence composed of cohesive shallow units, interbedded sands, and a dense sand horizon at depth.

To facilitate interpretation of this vertical organization, the CPTu results were grouped into five units on the basis of their geotechnical response and SBTn classification (Table 3). Units I and IV correspond predominantly to cohesive materials, including clays, clayey silts, and organic soils; Units II and V represent the main sandy intervals, ranging from sands and silty sands to dense sand; and Unit III defines an intermediate transition zone characterized by mixed sand–clay textures. This classification indicates that the El Pal-

mar subsurface is vertically heterogeneous rather than homogeneous, with alternating fine-grained and permeable intervals of direct relevance to induced infiltration and well design. The complete normalized CPTu profiles for CPTu-DR-01, including normalized cone resistance, normalized friction ratio, normalized pore pressure ratio, soil behavior type index, and the normalized soil behavior type according to Robertson's Qtn–Fr-based classification, are provided in Supplementary Figure S1. It is important to note that Unit V is a very thin dense sand interval in the CPTu-DR-01 sounding and should not be interpreted by itself as a sufficient long-term abstraction horizon. Rather, it provides local evidence of a deeper permeable interval that must be considered together with the overlying sandy and mixed units, the ERT-derived resistivity geometry, and future hydraulic testing before defining the final well-screen depth and expected abstraction capacity.

Table 3. Local stratigraphic and geotechnical classification of the subsurface at CPTu-DR-01 in the El Palmar sector based on CPTu parameters and the SBTn index. Qtn: normalized cone resistance; Fr: normalized friction ratio; Bq: normalized pore pressure ratio ($\Delta u/q_n$); Ic: soil behavior type index; SBTn: normalized soil behavior type according to Robertson's Qtn–Fr-based classification. Unit V represents a thin local dense sand interval in CPTu-DR-01 and should be interpreted as supporting evidence of deeper permeable conditions rather than as a standalone abstraction target.

Unit	Depth (m)	Qtn	Fr (%)	Bq	Ic	SBTn Classification
I	0.0–6.5	10–30	2.0–6.0	0.2–0.5	>3.0	Clays and clayey silts
II	6.5–9.5	60–120	<2.0	≈0	1.5–2.5	Sands and silty sands
III	9.5–18.5	20–150	2.0–6.0	0.0–0.2	2.0–3.5	Sand-to-clay mixtures
IV	18.5–28.5	<20	3.0–10.0	0.4–0.9	>3.2	Clays and organic soils
V	28.5–29.0	>300	<1.5	≈0	<1.3	Dense sand

3.6. Hydrodynamic Conditions of the River Channel

Liquid discharge measurements, together with topographic and bathymetric surveys, were conducted in July 2025 in the El Palmar sector at two measurement points (Point A and Point B). These measurements correspond to a single field campaign during the mid-year hydrological period in a region characterized by bimodal rainfall seasonality, and indicated high flows, mean depths on the order of 4 m, and moderate velocities (Table 4).

Table 4. Geometric and hydraulic parameters measured in the El Palmar sector.

Parameter	Point A	Point B
Section width (m)	86.63	80.47
Mean depth (m)	4.62	3.92
Mean velocity (m/s)	0.67	0.95
Mean discharge (m^3/s)	257.41	253.73

Topographic, bathymetric, and field observations of the evaluated river reach did not indicate evidence of intense erosive activity, active lateral migration, or marked channel instability at the project scale. Instead, the surveyed sections were consistent with a relatively stable alluvial channel geometry, which is favorable for RBF implementation because it reduces the likelihood of structural exposure, scour, or rapid burial of future abstraction infrastructure.

3.7. Dynamic Subsurface Conditions and Constraints for System Implementation

Passive seismic profiles showed shear-wave velocity (Vs) values of approximately 140–160 m/s within the first 9 m of depth, increasing progressively to 200–300 m/s at depths close to 35–40 m. This pattern is characteristic of fine- to intermediate-textured soils

with high porosity and low cementation [46]. The corresponding phase velocity–frequency dispersion image and the inverted 1D Vs model for seismic line MAM-1 are provided in Supplementary Figures S2 and S3, respectively. The relatively low Vs values indicate a poorly consolidated alluvial sequence with gradual stiffness increase with depth; however, these data provide mechanical context only and do not demonstrate long-term preservation of pore structure, hydraulic conductivity, or filtration capacity during RBF operation [47].

3.8. Hydraulic and Sedimentary Conditions of the River Channel

Hydraulic measurements and channel-condition observations conducted during the July 2025 field campaign at El Palmar and La Esperanza indicated an alluvial plain river system with mean flows between 254 and 257 m^3/s and fine-sediment loads with mean concentrations of approximately 275 mg/L at El Palmar and 394 mg/L at La Esperanza. Suspended sediment concentrations were generally within a range of approximately 200 to 500 mg/L. Bed-material observations indicated a predominance of fine sands, with the fraction of particles smaller than 0.075 mm remaining below approximately 15–25%. Although these data do not allow for the calculation of clogging rates, they provide a basis for defining preliminary operational scenarios. Suspended sediment concentrations near the lower part of the observed range would represent baseline filtration conditions, whereas concentrations approaching the upper range of approximately 500 mg/L would represent higher-risk periods in which riverbed clogging, head-loss development, and maintenance requirements could increase substantially.

3.9. Integration of Factors as Criteria for Locating an RBF System

The final selection of El Palmar was based on the convergence of the sequential screening criteria rather than on a numerical score: VES identified the most favorable depth and interpreted continuity of potentially permeable units among the four sectors; ERT provided profile-scale geometric support by showing resistivity domains traceable along the 168 m transect, including an upper domain laterally traceable over approximately 120 m; CPTu supported the interpretation of alternating filtering and transmitting layers; passive seismic data indicated a mechanically consistent, poorly consolidated alluvial sequence; and river-reach observations showed high discharge, moderate velocities, relative channel stability, and sediment conditions that represent a design constraint rather than an exclusion factor. The spatial consistency among identified alluvial thickness, inferred bed permeability, and hydraulic stability of the channel supported the identification of zones where the hydrostratigraphic and river-reach conditions are compatible with potential induced recharge processes, although direct river–aquifer connectivity was not measured through piezometric, hydraulic-gradient, pumping-test, or tracer-based evidence.

Accordingly, the results should be interpreted as evidence of preliminary site suitability and prioritization for future validation, not as a final demonstration of aquifer transmissivity, sustainable yield, or operational river–aquifer exchange under pumping conditions. Similarly, the study does not demonstrate induced infiltration rates, bank-filtrate fraction, subsurface residence time, or treatment performance; it only identifies hydrostratigraphic and river-reach conditions that are compatible with the future testing of these processes. Because the second-stage characterization was intentionally concentrated at El Palmar after the VES screening, the comparison among sectors should be interpreted as a staged prioritization under unequal data density, and not as a fully equivalent site-by-site engineering comparison.

4. Discussion

4.1. Geoelectrical Differentiation of Favorable and Unfavorable Sectors for RBF

The contrast among the geoelectrical sections in Figure 4, together with the resistivity-based interpretation framework summarized in Table 1 and the sector-specific values compiled in Table 2, indicates that El Palmar is the sector where the subsurface configuration combines moderate resistivity values, favorable depth, and the strongest available profile-scale evidence of geometric continuity, including resistivity domains traceable along the ERT transect, in a manner consistent with a technically viable RBF target. In particular, the El Palmar profile ELPAL-3 showed resistivity values between 52 and 61 Ω·m from approximately 10 to 100 m depth, which fall within the range interpreted as permeable sandy to gravelly alluvial materials. However, the prioritization of El Palmar was not based on ELPAL-3 alone. Rather, ELPAL-3 was treated as the most favorable local expression within a sector that also presented favorable surface conditions for detailed investigation, including flat topography, comparable climatic forcing, and no evident geomorphic discontinuity that would suggest a separate hydrogeological setting within the candidate reach.

Interpretation of subsurface material as a function of electrical resistivity should not be treated as universal, but rather validated using expert hydrogeological judgment, borehole information, and local geological context. Resistivity values are inherently non-unique, and similar or overlapping intervals may correspond to different materials in different settings. For example, [48] reported overlapping resistivity ranges for clayey/shaly sand (283–524 Ω·m), medium-grained sand (180–327 Ω·m), and clayey sand (424–718 Ω·m), demonstrating that lithological interpretation cannot rely on resistivity alone and must be constrained by site-specific stratigraphic and hydrogeological evidence. Accordingly, lithological labels such as sands, gravels, silts, or clays should be read as interpreted hydrostratigraphic classes constrained by local geological reasoning and supporting field evidence, not as direct lithological observations from borehole logging. Therefore, the 52–61 Ω·m interval identified at ELPAL-3 was treated as a locally constrained indicator of potential permeable alluvial material only when interpreted together with depth, geometry, geomorphological position, and the supporting ERT and CPTu evidence, not as a standalone diagnostic threshold.

This pattern contrasts sharply with the behavior observed in Candelaria, where resistivity values were consistently low and only one VES was considered sufficient because the sector was dominated by clayey and silty materials. Such materials are widely recognized as unfavorable for induced infiltration because they limit hydraulic conductivity, reduce river–aquifer connectivity, and increase the risk of local clogging [49,50].

La Esperanza and Cayetana represent intermediate but still less favorable cases. In both sectors, the geoelectrical sections indicate the presence of fine-grained materials in the shallow and intermediate subsurface, while the units interpreted as sands and gravels occur only at depths greater than about 90 m (Table 2; Figure 4b,c). From a strictly hydrogeological standpoint, the presence of deep permeable units does not automatically make a site suitable for RBF. For this technology, the productive zone must not only be permeable but also hydraulically accessible, laterally connected, and economically drillable [6,51]. In this sense, the results show that the main limitation in La Esperanza, Candelaria, and Cayetana is not the total absence of coarse deposits, but rather their unfavorable geometry and depth. This interpretation is also conservative because deeper VES-derived layers are less vertically resolved than shallower intervals; therefore, the occurrence of permeable units at greater depth was treated as a broad indication of reduced practical suitability rather than as a precise estimate of exploitable aquifer geometry. This also explains the Candelaria result in Table 2: the 103.80 Ω·m interval was treated as an isolated deeper layer of potential interest, but not as sufficient evidence of site suitability because it was not associated with a

shallow-to-intermediate, laterally supported permeable target comparable to that observed at El Palmar.

In practice, targeting these deep permeable horizons would require substantially greater drilling and pumping effort and could encounter less favorable water quality, so they are not considered realistic RBF objectives under the design conditions examined here. This distinction is important because it moves the interpretation away from a binary "suitable/unsuitable" view and toward a more realistic assessment of relative feasibility based on the hydraulic architecture of the alluvial system.

4.2. Hydrostratigraphic Controls on Induced Infiltration and Well Design in the El Palmar Sector

Once El Palmar was identified as the most favorable sector, the electrical tomography and CPTu results provided a much more detailed basis for interpreting the local hydrostratigraphy and assessing its implications for RBF design. Figure 5 shows that the subsurface in El Palmar is not uniformly coarse, but rather organized into at least two hydrogeologically distinct domains: an upper unit with lower resistivity values, interpreted as a sandy-silty alluvial body, and a deeper unit with higher resistivity values, interpreted as sands and gravels. The upper unit extends through the first approximately 25 m and was laterally traceable over roughly 120 m along the selected ERT transect, whereas the deeper unit appears as a coherent higher-resistivity body within the same profile. From a treatment perspective, this shallow sandy–silty interval may function as a potential natural pretreatment zone rather than as a preferred depth for well screens, although this role remains hypothetical until water-quality evolution, residence time, and redox conditions are evaluated under induced-flow conditions. This configuration is significant because it suggests a possible functional stratification in which the shallow deposits could contribute to the filtration and retardation of induced flow, while the deeper deposits represent the main interval of hydrogeological interest for future abstraction testing.

The CPTu-based stratigraphic classification in Table 3 reinforces this interpretation by showing that the El Palmar subsurface is organized into alternating cohesive, transitional, and sandy units rather than a single uniform alluvial body. In particular, the predominance of clays, clayey silts, and organic soils in Units I and IV contrasts with the sandy character of Units II and V, while Unit III represents an intermediate mixed-texture interval. This vertical arrangement suggests a shallow sequence that may partially restrict vertical infiltration and a deeper permeable horizon that is more appropriate for well screen placement. The occurrence of organic-rich clays within Units I and IV also indicates a potential geochemical risk, as such horizons may favor anoxic conditions and the mobilization of Fe and Mn, with possible consequences for abstracted-water quality. This has direct design implications. On the one hand, the presence of fine to intermediate sediments in the upper section may be advantageous because such materials can improve water quality through physical attenuation and filtration during subsurface passage [52]. On the other hand, these same layers may also reduce the infiltration rates if they are too thick or too continuous, especially if shallow clogging is developed in the river bottom during operation.

This dual role of the shallow unit is one of the most important findings of the study. The results do not support a simplistic interpretation in which fine-grained layers are viewed only as negative. Instead, the combined evidence from Figure 5 and Table 3 suggests that the upper sandy-silty unit may have a potential pretreatment role, whereas the deeper sand-and-gravel-bearing intervals represent the principal hydrogeological objective for future abstraction; however, the treatment function of the shallow unit should be tested through water-quality monitoring, travel-time analysis, and redox evaluation during pilot-scale operation. This interpretation is consistent with previous studies showing that the efficiency of RBF systems depends not merely on the existence of permeable horizons,

but on the internal arrangement of filtering and transmitting layers, the thickness of fine-grained intervals, and the extent to which these intervals control residence time, clogging susceptibility, and redox evolution [1,5,53].

At the same time, Table 3 shows that the permeable units identified in CPTu-DR-01 are neither thick nor laterally infinite, which introduces an important design constraint. The horizon classified as sands and silty sands in Unit II appears promising but limited in thickness, whereas Unit V corresponds to a very thin dense sand interval at approximately 28.5–29.0 m. Therefore, Unit V should not be interpreted as a standalone abstraction horizon capable of sustaining long-term pumping. Its significance is instead diagnostic: it supports the presence of deeper permeable material within the local stratigraphic sequence and helps constrain the vertical position of potential target intervals. Consequently, RBF feasibility at El Palmar depends on precise screen placement, possible interaction among multiple sandy or mixed-texture intervals, avoidance of the most clay-rich layers, and future pumping or abstraction tests to quantify sustainable yield. In this sense, the hydrostratigraphic results derived from Figure 5 and Table 3 provide a first-order framework for design, but not a final estimate of long-term abstraction capacity.

4.3. Hydraulic, Geomorphological, and Mechanical Conditions Controlling System Feasibility

The hydraulic and geomorphological characterization of the Cauca River in the El Palmar sector adds a second critical dimension to the suitability analysis. Table 4 shows that the evaluated river reach is characterized by high mean discharges, with values of 257.41 and 253.73 m^3/s at the two measured sections, mean depths of 4.62 and 3.92 m, and moderate velocities of 0.67 and 0.95 m/s. Because these values were obtained during a single July 2025 field campaign, they should be interpreted as a snapshot of the hydraulic condition during the mid-year hydrological period rather than as a complete representation of seasonal variability in the Cauca River. These values indicate that the river has both sufficient water availability and the hydraulic energy needed to sustain river–aquifer exchange [54,55]. This is particularly relevant in the context of the stratigraphic limitations identified in the shallow subsurface, because favorable hydraulic gradients may partly compensate for moderate permeability in the upper alluvial layers and help sustain induced infiltration even where fine sediments are present. The absence of clear evidence of intense erosion or active lateral channel migration further strengthens this interpretation, suggesting that the selected reach has relative geomorphological stability at the project scale. This stability is important because channel instability can compromise RBF operation by causing burial, scour, or the exposure of abstraction structures.

Sediment-related conditions of the channel also deserve careful interpretation. The mean suspended-solid concentrations were on the order of 275 mg/L in El Palmar and 394 mg/L in La Esperanza, with typical values of approximately 200–500 mg/L for suspended loads in the evaluated reach. In addition, channel-bed material was dominated by fine sands, with less than approximately 15–25% of particles smaller than 0.075 mm. These data indicate a hydraulically active alluvial river with substantial fine-sediment transport [19,56,57]. From an RBF perspective, this is a condition of both opportunity and risk. The presence of predominantly sandy bed materials suggests that the riverbed initially has connected intergranular porosity and therefore a potentially favorable permeability for induced infiltration [56]. However, the suspended load indicates that this favorable condition may be progressively altered by superficial clogging at the sediment–water interface, especially during prolonged operation or under periods of elevated sediment input [49,58,59]. In operational terms, the lower part of the observed suspended-load range may correspond to baseline operating conditions, whereas concentrations approaching approximately 500 mg/L should be regarded as higher-risk periods for clogging develop-

ment, head-loss increase, reduction in infiltration capacity, and more frequent maintenance or operational adjustment. Because no clogging-rate measurements, infiltration tests, or temporal turbidity monitoring were available, this scenario-based interpretation should be considered preliminary. The results therefore support an interpretation in which sediment load is not an exclusion factor, but a design and maintenance constraint that must be explicitly evaluated during the pilot-scale phase.

The passive seismic data provide a third line of evidence for characterizing the physical setting of El Palmar, but their interpretation should remain limited to mechanical context. The reported Vs values of approximately 140–160 m/s in the first 9 m, increasing to 200–300 m/s at 35–40 m depth, are consistent with poorly consolidated alluvial materials that become progressively stiffer with depth. This pattern does not indicate abrupt mechanical discontinuities within the investigated depth range and is compatible with a relatively gradual alluvial sequence. Under ambient vibration conditions, such a medium is expected to respond predominantly elastically, without major rearrangement of the pore network or progressive loss of hydraulic conductivity [46,47,60]. However, passive seismic data alone cannot demonstrate the long-term preservation of pore structure, hydraulic conductivity, or filtration capacity under pumping-induced hydraulic gradients. Therefore, these results should be interpreted as supporting evidence of the local mechanical setting, and not as proof of long-term operational stability. The hydraulic and structural behavior of the filtering medium must be verified during pilot-scale operation through abstraction tests, hydraulic monitoring, and the assessment of changes in infiltration capacity over time.

4.4. Integrated Interpretation as a Basis for Technically Defensible Site Selection

A major contribution of this study is that it demonstrates the value of integrating geoelectrical, geotechnical, hydraulic, river-channel, and passive seismic information into a single site-selection framework. The results show that no individual parameter would have been sufficient to identify the most favorable sector with adequate confidence. For example, Table 2 alone might suggest that La Esperanza, Candelaria, and Cayetana still contain coarse materials of potential interest; however, when these data are interpreted together with Figure 4, their excessive depth and the dominance of fine-grained overlying units become evident. Likewise, El Palmar appears favorable from the VES data, but its real hydrogeological significance becomes much clearer only after considering the lateral continuity revealed by Figure 5, the hydrostratigraphic detail provided by Table 3, the hydraulic context summarized in Table 4, and the additional mechanical context derived from passive seismic measurements. Accordingly, ELPAL-3 was used as a key screening indicator of the most favorable local window within El Palmar, but the sector-level prioritization depended on the convergence between this VES response and the subsequent local ERT, CPTu, passive seismic, and river-reach evidence.

This integrated perspective also improves the conceptual understanding of what makes a site suitable for RBF in a tropical alluvial river setting. The favorable site is not simply the one with the highest resistivity values, the coarsest materials, or the largest discharge. Instead, it is the one where multiple factor converge: permeable deposits at manageable depth, sufficient lateral continuity, a shallow sequence that can contribute to filtration without completely suppressing infiltration, a river reach capable of maintaining hydraulic gradients, a geomorphologically stable channel, and a subsurface with mechanical properties compatible with poorly consolidated alluvial deposits [29,36,61,62]. By that standard, El Palmar is the sector in which the combined evidence supports a better RBF implementation.

This integrated interpretation is also the point where the discussion moves beyond a simple comparison of sites. Our results show that the selection of an RBF site in the RUT

district must be grounded in multiscale physical evidence. The study therefore provides a technically defensible basis for prioritizing El Palmar as the most suitable sector, at least under the current design objective of implementing an efficient and operationally feasible RBF system for agricultural irrigation. The unequal level of field investigation among sectors should be considered when interpreting the final prioritization. Because ERT, CPTu, passive seismic, and detailed river-reach characterization were concentrated in El Palmar, the study does not provide the same level of engineering detail for La Esperanza, Candelaria, and Cayetana. However, this does not invalidate the screening result, because the decision to intensify the investigation at El Palmar was made after the comparative VES stage had already shown that the other sectors were less favorable due to shallow fine-grained dominance or a deeper occurrence of units interpreted as sands and gravels. Therefore, the conclusion should be interpreted as follows: El Palmar is the best-supported priority sector based on the available staged evidence, while complete exclusion or final engineering rejection of the other sectors would require equivalent detailed investigations.

A related limitation is the spatial density of the VES survey relative to the length and heterogeneity of the evaluated river corridor. Ten VES points across four sectors cannot capture all lateral facies changes expected in a tropical alluvial plain. Consequently, the geoelectrical sections should not be interpreted as continuous aquifer-scale models. Their role in this study was more restricted: to provide a first-order comparison among candidate sectors and to identify where detailed characterization would be most technically justified. This limitation is especially relevant for Candelaria, where the decision not to proceed to second-stage characterization was based on a single unfavorable VES response; therefore, Candelaria should be regarded as a lower-priority sector under the available screening evidence rather than as a definitively unsuitable sector. This limitation is particularly important for future design stages, where additional ERT profiles, borehole control, pumping tests, piezometric monitoring, and riverbed hydraulic measurements would be required to refine well location and engineering parameters. Similarly, the single ERT profile at El Palmar should be interpreted as local evidence of lateral continuity along the selected transect, not as a complete two-dimensional representation of the entire sector.

Another limitation concerns the reporting of geoelectrical inversion diagnostics. Because detailed inversion metrics, including RMS error, convergence criteria, model sensitivity, and alternative inversion solutions, were not available for inclusion, the resistivity sections should not be interpreted as fully constrained quantitative models. Their value in this study lies in their use as comparative screening evidence for identifying broad hydrostratigraphic contrasts among sectors. For this reason, the final interpretation did not rely on resistivity alone, but on the consistency between geoelectrical patterns and independent field evidence, particularly the ERT-derived geometry at El Palmar, CPTu-based stratigraphic organization, passive seismic Vs structure, and river-reach hydraulic conditions. Future design-level investigations should include complete inversion diagnostics, uncertainty analysis, direct lithological control, and hydraulic testing to improve the reliability of the subsurface model.

A further limitation is that the present study did not include pumping tests, groundwater-level monitoring, hydraulic-gradient analysis, transmissivity estimation, or direct river–aquifer exchange measurements. Therefore, the hydrogeological basis for site suitability should be understood as inferential and screening-level. The evidence supports El Palmar as the most technically justified sector for subsequent pilot-scale validation, but it does not provide final design parameters such as sustainable abstraction rate, aquifer transmissivity, capture-zone geometry, travel time, or induced-bank-filtrate fraction. These parameters must be quantified during the next stage through piezometric

monitoring, pumping or abstraction tests, and hydraulic response analysis under controlled operating conditions.

Direct comparison with similar RBF case studies in tropical alluvial agricultural settings remains difficult because such studies are still limited, particularly in Latin America. Nevertheless, the El Palmar results are broadly consistent with the hydrogeological conditions reported in alluvial RBF applications where suitability depends on the coexistence of permeable sand or gravel-bearing units, sufficient saturated thickness, and river-channel conditions capable of sustaining induced infiltration. At the same time, the observed suspended-sediment concentrations and fine-sediment transport are more characteristic of tropical, high-turbidity river systems and should be considered a site-specific operational constraint rather than a universally favorable or unfavorable condition. Therefore, the resistivity ranges, sediment conditions, and aquifer geometry observed in this study should not be treated as generic thresholds for tropical RBF design, but as locally constrained indicators that support El Palmar as a priority site under the hydrogeomorphic conditions of the RUT district.

The next logical step is not additional broad screening, but focused pilot-scale validation at El Palmar, including direct confirmation of river–aquifer connectivity through piezometric monitoring, hydraulic-gradient evaluation, pumping or abstraction tests, seasonal hydraulic monitoring, well design optimization, riverbed clogging assessment under contrasting suspended-sediment conditions, monitoring of head-loss development and infiltration-capacity change, water-quality and redox monitoring, travel-time evaluation, residence time, bank-filtrate contribution, and temporal evaluation of treatment performance under real operating conditions.

Future RBF planning in the RUT should therefore be supported by locally validated field-scale information. This includes hydraulic and soil evidence relevant to irrigation decisions [63], as well as UAV-derived topographic products to refine river-reach morphology, microtopographic gradients, and abstraction-well positioning within the prioritized sector [64].

5. Conclusions

This study demonstrated that the identification of suitable locations for RBF in the RUT irrigation district requires an integrated evaluation of subsurface architecture, river hydrodynamics, and river-channel conditions rather than reliance on any single indicator. The combined interpretation of geoelectrical surveys, CPTu-derived stratigraphic information, passive seismic measurements, and hydraulic characterization made it possible to define the main controls on induced infiltration and to distinguish sectors with contrasting levels of suitability. In this sense, the principal contribution of the study is not only the description of local subsurface conditions, but the establishment of a technically consistent framework for RBF implementation in a tropical alluvial agricultural setting.

Among the four sectors evaluated, El Palmar was identified as the most favorable site for potential RBF implementation. This conclusion is supported by the occurrence of intermediate resistivity values (52–61 Ω·m), the lateral continuity of permeable units, and a stratigraphic configuration consisting of a shallow fine-grained layer overlying a deeper, continuous sand-and-gravel unit with better abstraction potential. This arrangement is particularly relevant because it combines shallow horizons that could potentially contribute to natural filtration and attenuation with deeper intervals of hydrogeological interest; however, both the treatment role of the shallow units and the long-term abstraction capacity of the deeper intervals must be confirmed through future water-quality monitoring, travel-time analysis, and pumping or abstraction tests. In contrast, La Esperanza, Candelaria, and Cayetana showed less favorable conditions due either to the predominance of clayey

and silty materials or to the presence of permeable layers only at depths greater than 90 m. From an engineering standpoint, these conditions substantially increase drilling depth, construction cost, operational demand, and overall design complexity.

The study also showed that hydraulic feasibility cannot be interpreted independently of channel conditions. In El Palmar, the Cauca River exhibited high discharge, moderate flow velocity, and relative geomorphological stability, all of which are favorable for sustaining hydraulic gradients between the river and the alluvial aquifer. These conditions strengthen the likelihood of induced recharge and support the functional viability of RBF in the selected sector. At the same time, the reported suspended sediment loads indicate that clogging risk should be treated as a design constraint rather than as an exclusion criterion, particularly during higher-risk periods when suspended sediment concentrations approach the upper observed range of approximately 500 mg/L. In other words, fine sediment transport does not invalidate the site, but it does require careful optimization of abstraction depth, well position relative to the river, and long-term operational management.

Finally, the passive seismic results suggest that the El Palmar subsurface is dominated by poorly consolidated alluvial materials with a gradual increase in stiffness with depth. This information provides useful mechanical context for interpreting the alluvial sequence, but it should not be considered evidence of the long-term preservation of pore structure or hydraulic conductivity during RBF operation. These aspects must be verified through pilot-scale abstraction tests, hydraulic monitoring, and the evaluation of infiltration-capacity changes over time. The evidence therefore supports El Palmar as the best-supported priority sector for future RBF pilot validation in the RUT district, rather than as a site with already demonstrated long-term operational performance. The next step should therefore be a pilot-scale validation under real operating conditions, with explicit monitoring of abstraction performance, clogging evolution, and water-quality response. Because the detailed characterization was intentionally concentrated in the sector prioritized by the initial VES screening, future studies should apply comparable ERT, CPTu, passive seismic, and hydraulic assessments to the remaining sectors if the objective is to produce a fully equivalent engineering comparison rather than a staged feasibility prioritization.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18121496/s1, Figure S1. Normalized CPTu classification profiles for CPTu-DR-01 at the El Palmar sector, including Qtn, Fr, Bq, Ic, and SBTn-based soil behavior type classification. Figure S2. Phase velocity–frequency dispersion image for passive seismic line MAM-1 at the El Palmar sector. Figure S3. Inverted 1D shear-wave velocity (Vs) model for passive seismic line MAM-1 at the El Palmar sector, showing low Vs values in the shallow alluvial sequence and a progressive increase in stiffness with depth.

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References

1. Ahmed, A.K.A.; Marhaba, T.F. Review on River Bank Filtration as an in Situ Water Treatment Process. *Clean Technol. Environ. Policy* **2017**, *19*, 349–359.
2. Sprenger, C.; Lorenzen, G.; Hülshoff, I.; Grützmacher, G.; Ronghang, M.; Pekdeger, A. Vulnerability of Bank Filtration Systems to Climate Change. *Sci. Total Environ.* **2011**, *409*, 655–663. [CrossRef] [PubMed]
3. Jaramillo, M. Riverbank Filtration: An Efficient and Economical Drinking-Water Treatment Technology. *Dyna* **2012**, *79*, 148–157.
4. Castillo-Sánchez, L.; Echeverri-Sánchez, A.F.; Sánchez Torres, L.D.; Quiroga-Rubiano, E.L.; Benavides-Bolaños, J.A. A Review of Riverbank Filtration with a Focus on Tropical Agriculture for Irrigation Water Supply. *Water* **2025**, *17*, 3169. [CrossRef]
5. Hoang, T.N.A.; Covatti, G.; Nguyen, D.V.; Börnick, H.; Grischek, T. Feasibility of Riverbank Filtration in Vietnam. *Sustain. Water Resour. Manag.* **2024**, *10*, 174. [CrossRef]
6. Hoang, N.A.T.; Covatti, G.; Grischek, T. Methodology for Evaluation of Potential Sites for Large-Scale Riverbank Filtration. *Hydrogeol. J.* **2022**, *30*, 1701–1716. [CrossRef]
7. Satyaji Rao, Y.R.; Vijay, T.; Siva Prasad, Y.; Singh, S. Development of River Bank Filtration (RBF) Well in Saline Coastal Aquifer. *J. Water Process Eng.* **2020**, *37*, 101478. [CrossRef]
8. Gueting, N.; Klotzsche, A.; van der Kruk, J.; Vanderborght, J.; Vereecken, H.; Englert, A. Imaging and Characterization of Facies Heterogeneity in an Alluvial Aquifer Using GPR Full-Waveform Inversion and Cone Penetration Tests. *J. Hydrol.* **2015**, *524*, 680–695. [CrossRef]
9. Zhu, L.; Gong, H.; Dai, Z.; Guo, G.; Teatini, P. Modeling 3-D Permeability Distribution in Alluvial Fans Using Facies Architecture and Geophysical Acquisitions. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 721–733. [CrossRef]
10. De Vet, W.W.J.M.; Van Genuchten, C.C.A.; Van Loosdrecht, M.C.M.; Van Dijk, J.C. Water Quality and Treatment of River Bank Filtrate. *Drink. Water Eng. Sci.* **2010**, *3*, 79–90. [CrossRef]
11. Abd-Elaty, I.; Kuriqi, A.; Ganayem, H.M.; Ahmed, A.; Saleh, O.K.; Garrote, L. Assessment of Riverbank Filtration Performance for Climatic Change and a Growing Population. *Front. Environ. Sci.* **2023**, *11*, 1136313. [CrossRef]
12. Oberleitner, D.; Stütz, L.; Schulz, W.; Bergmann, A.; Achten, C. Seasonal Performance Assessment of Four Riverbank Filtration Sites by Combined Non-Target and Effect-Directed Analysis. *Chemosphere* **2020**, *261*, 127706. [CrossRef] [PubMed]
13. Vargha, M.; Róka, E.; Erdélyi, N.; Németh, K.; Nagy-Kovács, Z.; Kós, P.B.; Engloner, A.I. From Source to Tap: Tracking Microbial Diversity in a Riverbank Filtration-Based Drinking Water Supply System under Changing Hydrological Regimes. *Diversity* **2023**, *15*, 621. [CrossRef]
14. Hunt, H.; Schubert, J.; Ray, C. Conceptual Design of Riverbank Filtration Systems. In *Riverbank Filtration*; Ray, C., Melin, G., Linsky, R.B., Eds.; Springer: Dordrecht, The Netherlands, 2002; Volume 43.
15. Castillo-Sánchez, L.; Echeverri Sánchez, A.F.; Carreño Sánchez, M.M.; Barona Ramirez, S.M.; Jaramillo, M.F. Assessment of the Hazards Associated with Water Quality for Irrigation in the Environmental Interceptor Canal of the RUT District, Colombia. *Rev. Fac. Nac. Agron. Medellín* **2026**, *79*, e120876. [CrossRef]
16. ASORUT. Asociación de Usuarios Del Distrito de Adecuación de Tierras de Los Municipios de Roldanillo, La Unión, Toro. ASORUT. Available online: https://asorut.com/ (accessed on 15 May 2026).
17. Castillo-Sánchez, L. Evaluación de Los Peligros Asociados a La Calidad Del Agua Del Canal Interceptor Usada En Riego En El Distrito RUT. Master's Thesis, Universidad del Valle, Cali, Colombia, 2024.
18. Castillo-Sánchez, L. Zonificación Del Comportamiento Espacial de Las Propiedades Hidrodinámicas Del Suelo En El Distrito de Riego RUT. Master's Thesis, Universidad Nacional de Colombia (Palmira), Palmira, Colombia, 2016.

19. Gutiérrez, J.P.; Van Halem, D.; Rietveld, L. Riverbank Filtration for the Treatment of Highly Turbid Colombian Rivers. *Drink. Water Eng. Sci.* **2017**, *10*, 13–26. [CrossRef]
20. Galvis, M. Prospección Geoeléctrica Del Recurso Hídrico Subterráneo En La Vereda La Ramada, Sogamoso, Boyacá. Bachelor's Thesis, Universidad Pedagógica y Tecnológica de Colombia, Sogamoso, Colombia, 2016.
21. Adeeko, T.; Nordiana, M. Utilizing 2-D Electrical Resistivity Imaging (ERI) to Investigate Groundwater Potential. *Eur. J. Electr. Eng.* **2018**, *20*, 23–34. [CrossRef]
22. Loke, M.H.; Chambers, J.E.; Rucker, D.F.; Kuras, O.; Wilkinson, P.B. Recent Developments in the Direct-Current Geoelectrical Imaging Method. *J. Appl. Geophys.* **2013**, *95*, 135–156. [CrossRef]
23. Durán-Barón, M. Caracterización Geofísica de Acuíferos Por Medio de Técnicas de Prospección Geoeléctricas En El Municipio de Tibaná, Boyacá. Bachelor's Thesis, Universidad de los Andes, Bogotá, Colombia, 2024.
24. dos Santos Gomes, J.L.; Vieira, F.P.; Hamza, V.M. Use of Electrical Resistivity Tomography in Selection of Sites for Underground Dams in a Semiarid Region in Southeastern Brazil. *Groundw. Sustain. Dev.* **2018**, *7*, 232–238. [CrossRef]
25. Hiscock, K.M.; Grischek, T. Attenuation of Groundwater Pollution by Bank Filtration. *J. Hydrol.* **2002**, *266*, 139–144. [CrossRef]
26. Grischek, T.; Schoenheinz, D.; Ray, C. Siting and Design Issues for Riverbank Filtration Schemes. In *Riverbank Filtration*; Ray, C., Melin, G., Linsky, R.B., Eds.; Springer: Dordrecht, The Netherlands, 2002; Volume 43, pp. 291–302.
27. Jiang, Y.; Zhang, J.; Zhu, Y.; Du, Q.; Teng, Y.; Zhai, Y. Design and Optimization of a Fully-Penetrating Riverbank Filtrationwell Scheme at a Fully-Penetrating River Based on Analytical Methods. *Water* **2019**, *11*, 418. [CrossRef]
28. Li, W.; Nzeribe, B.N.; Liu, G.R.; Yao, G.; Crimi, M.; Rubasinghe, K.; Divine, C.; Mcdonough, J.; Wang, J. Modeling, Simulation and Analysis of Groundwater Flow Captured by the Horizontal Reactive Media Well Using the Cell-Based Smoothed Radial Point Interpolation Method. *Adv. Water Resour.* **2022**, *160*, 104089. [CrossRef]
29. Ghodeif, K.; Grischek, T.; Bartak, R.; Wahaab, R.; Herlitzius, J. Potential of River Bank Filtration (RBF) in Egypt. *Environ. Earth Sci.* **2016**, *75*, 671. [CrossRef]
30. Sandhu, C.; Grischek, T.; Kumar, P.; Ray, C. Potential for Riverbank Filtration in India. *Clean Technol. Environ. Policy* **2011**, *13*, 295–316. [CrossRef]
31. Woessner, W.W.; Poeter, E.P. *Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow*; The Groundwater Project: Waterloo, ON, Canada, 2020. [CrossRef]
32. Maiti, S.; Erram, V.C.; Gupta, G.; Tiwari, R.K. ANN Based Inversion of DC Resistivity Data for Groundwater Exploration in Hard Rock Terrain of Western Maharashtra (India). *J. Hydrol.* **2012**, *464–465*, 294–308. [CrossRef]
33. Palacky, G.J. Electromagnetic Methods in Applied Geophysics. In *Resistivity Characteristics of Geologic Targets*; Nabighian, M.N., Ed.; Geological Survey of Canada: Ottawa, ON, Canada, 1988; Volume 1, pp. 52–129.
34. Lévesque, Y.; Walter, J.; Chesnaux, R.; Dugas, S.; Noel, D. Electrical Resistivity of Saturated and Unsaturated Sediments in Northeastern Canada. *Environ. Earth Sci.* **2023**, *82*, 303. [CrossRef]
35. Kazakis, N.; Vargemezis, G.; Voudouris, K.S. Estimation of Hydraulic Parameters in a Complex Porous Aquifer System Using Geoelectrical Methods. *Sci. Total Environ.* **2016**, *550*, 742–750. [CrossRef] [PubMed]
36. Vogelgesang, J.A.; Holt, N.; Schilling, K.E.; Gannon, M.; Tassier-Surine, S. Using High-Resolution Electrical Resistivity to Estimate Hydraulic Conductivity and Improve Characterization of Alluvial Aquifers. *J. Hydrol.* **2020**, *580*, 123992. [CrossRef]
37. Shevnin, V.; Delgado-Rodríguez, O.; Mousatov, A.; Ryjov, A. Estimation of Hydraulic Conductivity on Clay Content in Soil Determined from Resistivity Data. *Geofísica Int.* **2006**, *45*, 195–207. [CrossRef]
38. Samouëlian, A.; Cousin, I.; Tabbagh, A.; Bruand, A.; Richard, G. Electrical Resistivity Survey in Soil Science: A Review. *Soil Tillage Res.* **2005**, *83*, 173–193. [CrossRef]
39. Lech, M.; Skutnik, Z.; Bajda, M.; Markowska-Lech, K. Applications of Electrical Resistivity Surveys in Solving Selected Geotechnical and Environmental Problems. *Appl. Sci.* **2020**, *10*, 2263. [CrossRef]
40. Rizk, S.; Anis, M.; Nazer, M.; Youssef, A.M.; Redwan, M.; El-Haddad, B.A. Environmental Hazards of Wastewater Disposal on Groundwater at the West Sohag Site, Egypt. *Sci. Rep.* **2025**, *15*, 36303. [CrossRef] [PubMed]
41. Kohno, M. Effects of Hydraulic Gradient and Clay Type on Permeability of Clay Mineral Materials. *Minerals* **2020**, *10*, 1064. [CrossRef]
42. Janik, K.; Rein, A.; Sitek, S. Towards Efficient Management of Riverbank Filtration Sites: New Insights on River-Groundwater Interactions from Environmental Tracers and High-Resolution Monitoring. *Hydrol. Earth Syst. Sci.* **2025**, *29*, 5893–5911. [CrossRef]
43. Zarif, F.M.; Elshenawy, A.M.; Barseem, M.S.M.; Al-Abaseiry, A.A.; Sayed, A.N.E. Evidence of Geoelectrical Resistivity Values on Groundwater Conditions in Wadi El Natrun and Its Vicinities, West Delta, Egypt (Cases Studies). *Sci. Rep.* **2022**, *12*, 10745. [CrossRef] [PubMed]
44. Stanly, R.; Yasala, S.; Murugesan, R.V. Hydrological Subsurface Investigation Using Geophysical Electrical and Magnetic Methods in and around Valliyar River Basin, India. *Results Geophys. Sci.* **2021**, *7*, 100022. [CrossRef]
45. Miller, R.B.; Heeren, D.M.; Fox, G.A.; Halihan, T.; Storm, D.E.; Mittelstet, A.R. The Hydraulic Conductivity Structure of Gravel-Dominated Vadose Zones within Alluvial Floodplains. *J. Hydrol.* **2014**, *513*, 229–240. [CrossRef]

46. Qiao, F.; Bo, J.; Qi, W.; Wang, L.; Chang, C.; Zhang, Z.; Wang, J. Study on the Dynamic Characteristics of Soft Soil. *RSC Adv.* **2020**, *10*, 4630–4639. [CrossRef] [PubMed]
47. Duan, W.; Cai, G.; Liu, S.; Puppala, A.J. Correlations between Shear Wave Velocity and Geotechnical Parameters for Jiangsu Clays of China. *Pure Appl. Geophys.* **2019**, *176*, 669–684. [CrossRef]
48. Okamkpa, J.R.; Igwe, O.; Onwuka, S.O.; Emedo, C.O.; Ezugwu, C.K.; Okonkwo, A.C. Determination of Aquifer Hydraulic Properties, Aquifer Potential and Vulnerability Characteristics Using Pumping Test and Surface Geophysical Data: A Case Study of Udi and Ezeagu Areas, Southeastern Nigeria. *Water Conserv. Sci. Eng.* **2024**, *9*, 60. [CrossRef]
49. Ulrich, C.; Hubbard, S.S.; Florsheim, J.; Rosenberry, D.; Borglin, S.; Trotta, M.; Seymour, D. Riverbed Clogging Associated with a California Riverbank Filtration System: An Assessment of Mechanisms and Monitoring Approaches. *J. Hydrol.* **2015**, *529*, 1740–1753. [CrossRef]
50. Przybyłek, J.; Dragon, K.; Kaczmarek, P.M.J. Hydrogeological Investigations of River Bed Clogging at a River Bank Filtration Site along the River Warta, Poland. *Geologos* **2017**, *23*, 201–214. [CrossRef]
51. Massmann, G.; Sültenfuß, J.; Dünnbier, U.; Knappe, A.; Taute, T.; Pekdeger, A. Investigation of Groundwater Residence Times during Bank Filtration in Berlin: A Multi-Tracer Approach. *Hydrol. Process.* **2008**, *22*, 788–801. [CrossRef]
52. Cui, G.; Liu, Y.; Su, X.; Tong, S.; Jiang, M. Aquifer Exploitation Potential at a Riverbank Filtration Site Based on Spatiotemporal Variations in Riverbed Hydraulic Conductivity. *J. Hydrol. Reg. Stud.* **2022**, *41*, 101068. [CrossRef]
53. Hu, B.; Teng, Y.; Zhai, Y.; Zuo, R.; Li, J.; Chen, H. Riverbank Filtration in China: A Review and Perspective. *J. Hydrol.* **2016**, *541*, 914–927. [CrossRef]
54. Schubert, J. Hydraulic Aspects of Riverbank Filtration-Field Studies. *J. Hydrol.* **2001**, *266*, 145–161.
55. Shebl, A.; Wahaab, R.A.; Elazizy, I.; Hagras, M. Hydraulic Performance of Riverbank Filtration: Case Study West Sohag, Egypt. *Water Supply* **2022**, *22*, 294–308. [CrossRef]
56. Grischek, T.; Bartak, R. Riverbed Clogging and Sustainability of Riverbank Filtration. *Water* **2016**, *8*, 604. [CrossRef]
57. Gutiérrez, J.P.; van Halem, D.; Uijttewaal, W.S.J.; del Risco, E.; Rietveld, L.C. Natural Recovery of Infiltration Capacity in Simulated Bank Filtration of Highly Turbid Waters. *Water Res.* **2018**, *147*, 299–310. [CrossRef] [PubMed]
58. Dubuis, R.; De Cesare, G. The Clogging of Riverbeds: A Review of the Physical Processes. *Earth Sci. Rev.* **2023**, *239*, 104374. [CrossRef]
59. Goldschneider, A.A.; Haralampides, K.A.; MacQuarrie, K.T.B. River Sediment and Flow Characteristics near a Bank Filtration Water Supply: Implications for Riverbed Clogging. *J. Hydrol.* **2007**, *344*, 55–69. [CrossRef]
60. Alnuaim, A.; Al-Mahbashi, A.M. Experimental Investigation for Shear Wave Velocity and Dynamic Characteristics of Unsaturated Sand–Clay Liners. *Sustainability* **2023**, *15*, 15681. [CrossRef]
61. Sebok, E.; Karan, S.; Engesgaard, P. Using Hydrogeophysical Methods to Assess the Feasibility of Lake Bank Filtration. *J. Hydrol.* **2018**, *562*, 423–434. [CrossRef]
62. Grischek, T.; Ray, C. Bank Filtration as Managed Surface-Groundwater Interaction. *Int. J. Water* **2009**, *5*, 125–139. [CrossRef]
63. Tafur-Hermann, H.; Osorio-Ocampo, E.; Echeverri-Sánchez, A.F.; Erazo-Mesa, E.; Benavides-Bolaños, J.A. Evaluating Method-Dependent Estimates of Volumetric Field Capacity in the Roldanillo–Unión–Toro Irrigation District, Colombia. *Water* **2026**, *18*, 1195. [CrossRef]
64. Benavides-Bolaños, J.A.; Guarín, D.; Drohan, P.J.; Bolkas, D.; Soto-Domínguez, A.P.Y. Unmanned Aerial Vehicle Photogrammetry for Mapping Hydrologically Sensitive and Phosphorus Critical Source Areas. *Comput. Electron. Agric.* **2026**, *247*, 111704. [CrossRef]

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