Groundwater, where are you? Insights through the lens of geophysics

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ABSTRACT
Groundwater scarcity has become a pressing concern worldwide, particularly in regions where overextraction, rapid population growth, and climate-driven changes are placing unprecedented stress on aquifer systems. This research story tells the importance of geophysics, particularly Direct Current (DC) resistivity methods, serve as a powerful, non-invasive tool for understanding subsurface conditions and locating groundwater resources. Resistivity surveys reveal subsurface conductivity variations that help identify water-bearing zones, map complex fracture networks, and monitor issues such as saltwater intrusion in coastal aquifers. With examples from coastal alluvial plain and lateritic formations, this research story tells the importance of modern multielectrode resistivity imaging in groundwater exploration, management, and sustainable use. As groundwater forms the backbone of the freshwater supply for millions, especially in coastal regions, this story underscores the urgent need for scientific methods, informed policies, and collective responsibility to ensure long-term water security.

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1. INDIA'S GROWING GROUNDWATER CRISIS

"How many times will I tell you to fill up the water tank on time?" a middle-aged man, Ram Prasad, shouted at his wife. He was a working professional and was getting late for his office. Again, he yelped, "It is an important day for me, and I am struggling for a bucket of water". "I don't know why the municipal water supply is not regular in our colony", his wife, Sita Devi, replied with tears in her eyes. After a few minutes of pin-drop silence, Ram Prasad left his office with middle-class frustration and many queries related to the jeopardised system, where he blamed himself for having voted for this government.

Hundreds of such conversations unfold every day in middle-class households, where everyone blames someone else for the water crisis. But who is really to blame? Do we really want to find out? Probably not, it's easier to sit comfortably at home, sip our coffee, and keep playing the blame game.

According to a study published in Science Advances (Jain et al., 2021), large parts of India are projected to face severe groundwater depletion by 2025, posing a major risk to national food security.

The NITI Aayog (2018) also warns that India is facing its most serious water crisis, with the demand for drinking water expected to exceed supply by 2030 unless corrective measures are implemented. This escalating situation underscores the urgent need for robust, evidence-based assessments of groundwater status at national and regional scales. National assessments show shifting groundwater availability across states and provide the latest estimates of dynamic groundwater resources used for policy planning (Central Ground Water Board, 2024). Thus, reliable subsurface investigation techniques become crucial for understanding the occurrence, distribution, and dynamics of groundwater systems. However, the question arises, how can we explore groundwater beneath the subsurface?

2. GEOPHYSICS AS A TOOL TO EXPLORE THE INVISIBLE SUBSURFACE

There is a saying by Kurt Vonnegut, "Science is a magic that works", and this magical tool of Geophysics helps us to see inside the Earth indirectly. Most people are curious to know the term "geophysics." Basically, "geo" means "earth," and physics principles help to explore it. It is like an X-ray machine of the Earth, where different electromagnetic, sound, and electrical waves travel through the Earth and bring hidden information to the surface.

Many people often wonder how geophysics can aid in groundwater exploration. The answer lies in the behaviour of water itself, as it is conductive; electrical current can pass through it easily. Thus, electrical resistivity or DC resistivity methods are among the most effective techniques for subsurface investigations.

Among various geophysical techniques such as seismic, GPR, electromagnetic, and gravity methods, electrical resistivity surveys remain the most effective for groundwater investigations. They provide high-resolution 2D subsurface images, allowing precise identification of multiple water-bearing zones (Fig. 1).

During my PhD, I was always curious about how geophysical methods reveal the presence of groundwater. In my early research years, I devoted significant time to studying the underlying physical principles, many of which initially seemed complex. However, once I began conducting field surveys, these concepts became clearer, and the mechanisms of groundwater detection through geophysics made perfect sense.

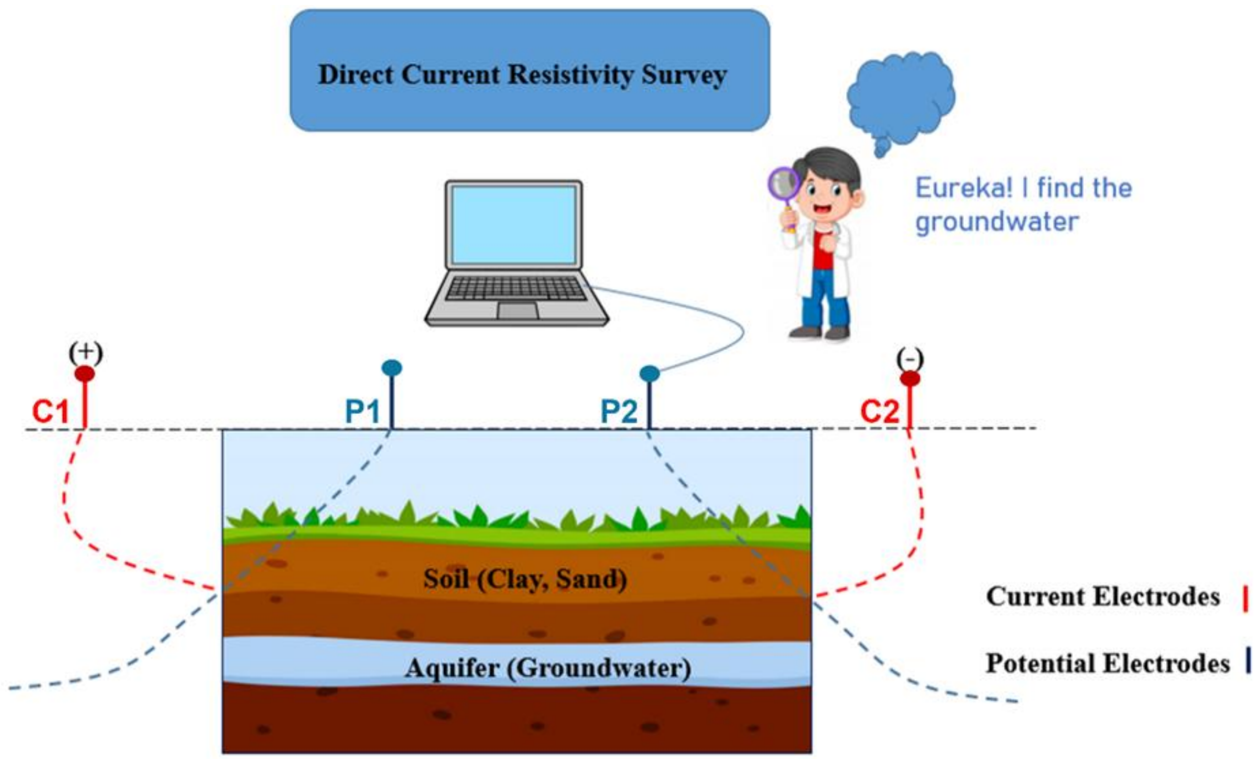

Figure 1. A schematic figure of DC resistivity survey for groundwater exploration (after Telford et al., 1990).

3. HOW GEOPHYSICS HELPS IN GROUNDWATER EXPLORATION

When we discuss geophysics, particularly DC resistivity, it relies on physics-based principles to identify the location of groundwater within the subsurface. The basic principle of the DC resistivity survey is straightforward. It uses a four-electrode configuration based on Ohm's law (Telford et al., 1990). An electric current is injected into the ground through two stainless-steel current electrodes, while the resulting potential difference is measured using two potential electrodes. The measurements are processed to generate resistivity images, which reveal conductive zones indicative of groundwater. Groundwater modifies the subsurface resistivity, influencing the measured potential values. By analysing these variations at the surface, we can interpret and map the distribution of groundwater beneath the Earth's surface.

In the early 1990s, a resistivity survey was conducted using a basic four-electrode setup; however, it was laborious and time-consuming. Thus, recent multielectrode resistivity surveys, also known as Electrical Resistivity Tomography (ERT), have gained popularity due to their robustness, fast data acquisition, and high-resolution images of the subsurface (Costall et al., 2018; Rupesh et al., 2021; Pradhan et al., 2022; Maurya et al., 2025; Tiwari et al., 2025). These images identify anomalous zones by mapping variations in subsurface resistivity, allowing clear detection of features such as groundwater-bearing layers, mineralized zones, and underground cavities (Asfahani and Radwan, 2021; Mondal et al., 2025; Zhang and Bishop, 2015).

As the application of ERT has expanded from field surveys to academic and training contexts, the emphasis has increasingly shifted toward improving data quality, survey design, and interpretation reliability. Standardized ERT acquisition and open datasets help users to learn how acquisition geometry and noise control influence subsurface images (Sinicyn et al., 2025).

Beyond standardized acquisition and data quality control, the reliability of DC resistivity interpretations ultimately depends on appropriate calibration and context-specific understanding of resistivity values. For DC resistivity method one important aspect is calibration as for Interpreting resistivity values requires local calibration. Recent alluvial studies report typical resistivity ranges and depth sensitivities used to distinguish sand, clay, and saturated layers (Daud et al., 2025). Thus, this method is useful for identifying the presence of subsurface groundwater. Geophysical techniques enable both qualitative and quantitative interpretation of groundwater conditions and can provide an initial assessment of areas experiencing groundwater depletion.

Overall, DC resistivity is a well-suited method for groundwater exploration. However, other geophysical methods such as seismic refraction, ground-penetrating radar, and electromagnetic techniques can also support groundwater investigations due to their sensitivity to groundwater and pore-fluid conditions. Each of these methods provides complementary information to resistivity surveys and can be very helpful in identifying groundwater. Seismic refraction is useful for estimating depth to bedrock, thickness of weathered layers, and identifying velocity contrasts between dry and saturated zones. This information helps in understanding aquifer geometry, especially in hard rock terrains (e.g., Telford et al., 1990; Reynolds, 2011). Ground-penetrating radar (GPR) provides very high-resolution images of shallow subsurface features such as soil layering, fractures, and preferential flow paths, particularly in dry, sandy, or lateritic environments where signal attenuation is low (Davis and Annan, 1989). Electromagnetic (EM) methods allow rapid mapping of subsurface conductivity over large areas and are effective for identifying zones related to groundwater presence, salinity, or clay content, especially in coastal and alluvial settings (McNeill, 1980; Palacky, 1988). While each of these methods has clear advantages, they are most effective when used in combination with DC resistivity rather than as standalone tools. In this manuscript, DC resistivity is retained as the primary method due to its robustness, depth penetration, and suitability across diverse geological settings, while the complementary techniques are briefly discussed to provide broader context and reduce interpretation uncertainty.

4. GROUNDWATER COMPLEXITY IN DIVERSE GEOLOGICAL AND COASTAL SETTINGS

Is groundwater really that easy to locate? Certainly not. In many regions, groundwater is concealed within complex fracture networks of hard-rock terrains, such as those in Andhra Pradesh and Karnataka. In contrast, in other settings it occurs within soft alluvial plains, including the Gangetic region of Uttar Pradesh, the coastal belts of Odisha, or within lateritic deposits of West Bengal (Fig. 2). These diverse hydrogeological conditions highlight the effectiveness of ERT as a reliable tool for identifying aquifer zones across varied environments. Moreover, recent ERT case studies from tectonically active basins further demonstrate the broad applicability of resistivity imaging for aquifer characterization beyond coastal and lateritic terrains (Takele et al., 2025). Further, numerous factors influence its quality and quantity, including less recharge, over-pumping, and contamination (Abanyie et al., 2023; Akhtar et al., 2021; Rusli et al., 2024). Climate also plays a significant role in the declining groundwater levels in India. Recent reductions in summer monsoon rainfall and increasing seasonal drying are accelerating groundwater depletion across parts of northern India, further intensifying the stress from excessive extraction (Mishra et al., 2024).

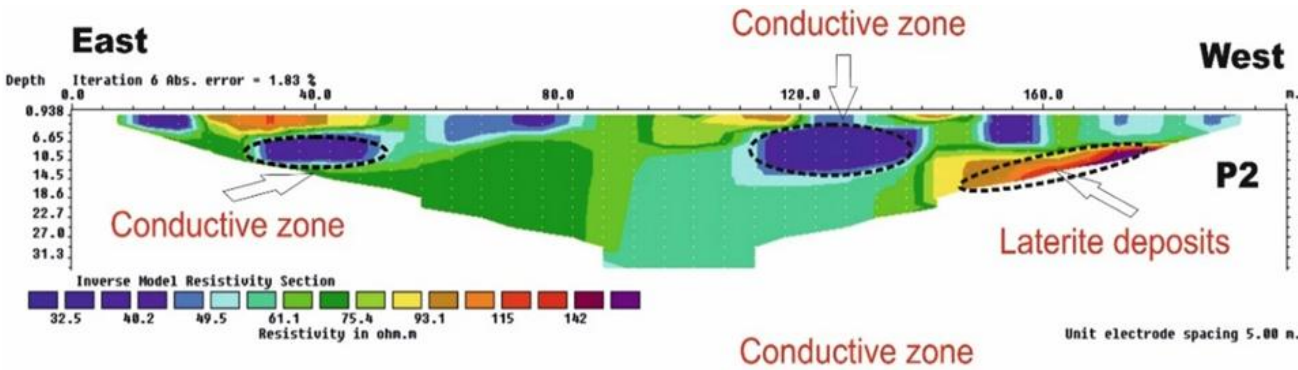

Figure 2. An example of a groundwater aquifer zone identified as a conductive anomaly in the laterite deposits of West Bengal, India (Rupesh et al., 2021).

Although DC resistivity surveys are commonly conducted in 2D mode, achieving a more complete volumetric understanding of subsurface heterogeneity increasingly requires 3D or quasi-3D ERT surveys, which are now widely practiced by researchers worldwide. This methodological progression from quasi-3D ERT applications in laterite terrains to integrated DC resistivity combined with numerical modeling, highlights recent advances in resolving the complexity of coastal aquifer systems (Rupesh et al., 2021; Tiwari et al., 2024; Tiwari et al., 2025).

Let us discuss the present world scenario. Approximately 37% of the world's population resides within 100 km of the coast, characterized by high population density. Due to their focal points for human settlement & various economic activities, coastal regions are always hotspots. Due to the increasing population in coastal regions, other activities such as agricultural expansion, economic development, and changing lifestyles (resulting in higher water use per capita) are creating enormous pressure on coastal groundwater resources.

5. TOWARDS SUSTAINABLE GROUNDWATER MANAGEMENT

In India, nearly 560 million people live along the coastal belts of Gujarat, Maharashtra, West Bengal, Andhra Pradesh, and several other states. With the country recognized as the world's largest extractor of groundwater (United Nations World Water Development Report, 2022), the pressure on this vital resource is immense. For many coastal communities, groundwater is the primary and often the only source of freshwater.

However, concerns about its quantity are growing, as increasing extraction threatens long-term sustainability by impacting both groundwater availability and replenishment.

Quality challenges add another layer of complexity. One of the most critical threats in coastal aquifers is saltwater intrusion (Fig. 3). Although driven naturally by the hydraulic connection between seawater and freshwater, this process has intensified due to human-induced stresses, especially over-pumping. Several factors contribute to the inland movement of saline water, including excessive groundwater withdrawal, tidal influences, recharge variability, long-term climatic fluctuations, flooding, artificial canal systems, and nearby salt-production activities. Researchers have combined DC resistivity surveys with laboratory experiments to identify the freshwater–saltwater interface. Field-based DC resistivity results, when corroborated with laboratory experiments and numerical models, can effectively delineate the freshwater–saltwater boundary even in highly heterogeneous coastal deposits (Tiwari et al., 2024).

Given the high cost of large-scale desalination, ensuring future water security for India's coastal communities depends on sustainable groundwater management that balances extraction with recharge and continuously monitors water quality. Recent case studies also emphasize that long-term groundwater sustainability hinges on institutional reforms and active community participation, underscoring the value of governance arrangements to local conditions (Shiferaw, 2024).

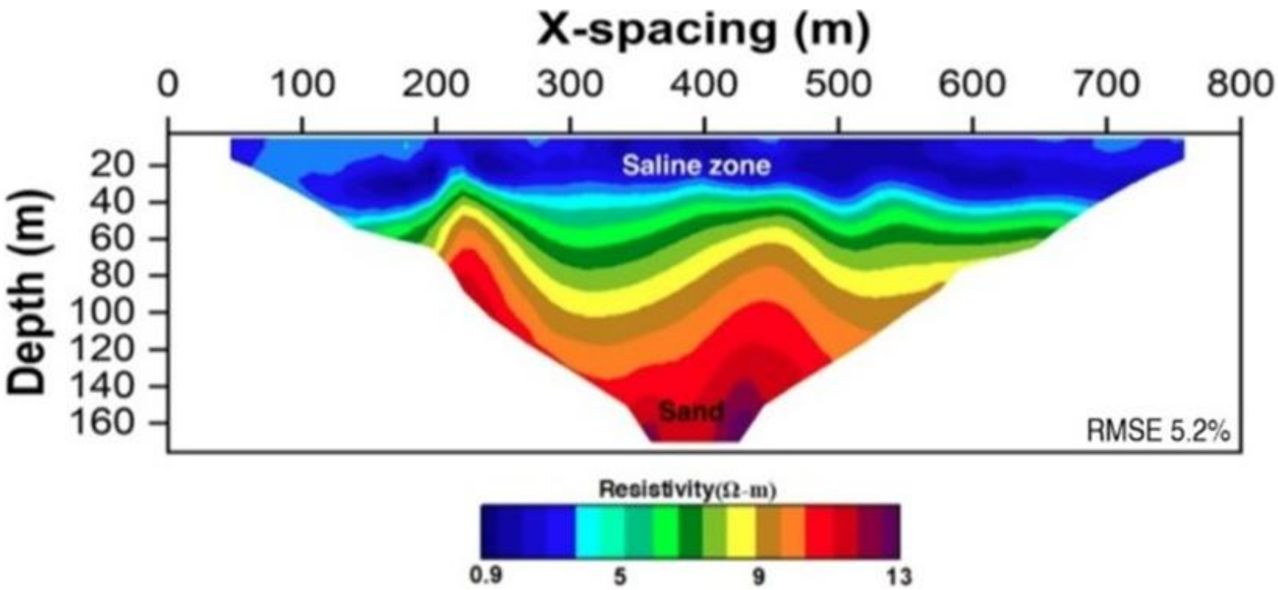

Figure 3. An example of saltwater intrusion near the coastal area of West Bengal, India (Tiwari et al., 2024).

When it comes to policies for borewells, the growing pressure on groundwater resources remains a significant challenge to achieving sustainability.

Along with policy measures, we must also explore the strategies for conserving our rapidly depleting groundwater resources. Geophysical surveys can play a key role by identifying potential recharge zones, enabling both shallow and deeper aquifers to be utilised more efficiently and sustainably over the long term. However, this is also a wake-up call for every citizen; responsible use of water is no longer optional, it is essential. Saving water today is the only way to secure our groundwater for tomorrow.

Thus, protecting groundwater requires a balanced approach that combines science, policy, and public awareness. Geophysical studies can support better planning, regulation, and recharge efforts by providing reliable information on subsurface conditions. When scientific knowledge guides policy and people use water responsibly, long-term groundwater sustainability becomes achievable. Safeguarding groundwater today is essential for ensuring water security for future generations.

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