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A global perspective on electrical resistivity tomography, electromagnetic and ground penetration radar methods for estimating groundwater recharge zones

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Accurate estimation of groundwater recharge is crucial for sustainable management of water resources. Various geophysical survey tools are used for groundwater recharge estimation and monitoring of these resources. This paper presents global perspectives of geophysical survey methods such as electrical resistivity tomography (ERT), electromagnetic (EM), and ground penetrating radar (GPR) for groundwater recharge estimation. About 93 papers were screened through PRISMA guidelines and were comprehensively analyzed including statistical metrics, configuration types, geological setting, investigation depth, limitations, and influencing factors. Temperate zones lead in geophysical surveys due to agriculture and interest has risen in mountainous and arid zones. The geological setting also affects the geophysical methods with ERT being the most favorable followed by EM and GPR. Investigation depth and different configurations were also studied. Influencing factors including subsurface heterogeneity and highly conductive soils often reduce resolution and distort signals particularly ERT, EM and GPR in conductive soils. Resistivity and EM measurements are affected by salinity and GPR signals by saturation. Data quality is affected by poor electrode-ground contact, topography, seasonal variability, frequency and cultural noise. Effectiveness and repeatability of geophysical survey methods are influenced by weather conditions and water table depth. Considering these factors, an adaptable and well-planned geophysical survey method selection in diverse geological setting can enhance the precision of groundwater recharge estimation. This paper aims to be the first scoping review on groundwater geophysical survey global perspectives, offering insights for future research.

KEYWORDS

groundwater recharge, geophysical surveys, hydro geophysics, electromagnetic, electrical resistivity tomography, ground penetrating radar, subsurface hydrology

1 Introduction

Groundwater resources play a critical role in sustaining agricultural productivity, ecosystem services and human livelihoods (Shaikh and Birajdar, 2024). The earth holds 1.4 billion km^3 of water, of which 3% is freshwater (Matta, 2010; Oksana and Dmytro, 2021). Out of the 3%, only 1% is accessible as surface fresh water whereas the rest 2% is locked in the form of ice caps and glaciers (Oswald Spring and Oswald Spring, 2019). Globally, groundwater serves as a drinking source for nearly 2 billion people which accounts for over one third of the world's population (Mukherjee et al., 2021). This water is not only important for human consumption, but for agricultural irrigation as well. Globally, 60–70% of groundwater is used for irrigation in agriculture (Wood and Cherry, 2021). The precise and accurate estimation of groundwater recharge is therefore necessary for sustainable utilization of groundwater and long-term sustainability planning (Ntona et al., 2022). However, groundwater recharge differs greatly in terms of time and space greatly influenced by climatic, geologic and anthropogenic factors which present significant challenges to direct measurements and mapping (Reinecke et al., 2020).

For hydrological balance and sustainability of subsurface regimes, groundwater recharge is the main determining factor (Amanambu et al., 2020). The alteration in global climate has had a significant influence on both the quantity and quality of groundwater recharge, even though it is controlled in parts through atmospheric processes like precipitation and evaporation (Cuthbert et al., 2019; Albuquerque et al., 2022). Thus, groundwater management and sustainability depend upon the spatiotemporal process of groundwater recharge (Amanambu et al., 2020; Judeh et al., 2021). The onsite determination of groundwater recharge is difficult, though some alternative indirect methods like empirical models and process-based models can be used for its estimation like electrical resistivity and electromagnetic surveys (Jourde and Wang, 2023). Nevertheless, traditional methods will lead to new sources of uncertainty when examining the impact of climate change on groundwater recharge (Aquilina et al., 2023). As per the Intergovernmental Panel on Climate Change (IPCC) projection, climate change will affect surface and subsurface groundwater resources (Smerdon, 2017), making it essential to assess its effects on groundwater recharge (Cuthbert et al., 2019). The influence of unpredictable precipitation patterns on recharge remains (Aslam et al., 2018). Factors like geophysical methods, general circulation models, and emission scenarios contributed to this uncertainty (Andaryani et al., 2023). Groundwater is primarily stored in aquifers at different depths based on location and age below the earth's surface which serve as a key natural resource (Fan et al., 2019; Cuthbert et al., 2019). Its detection and quantification are challenging due to subsurface variability (Lall et al., 2020; Aquilina et al., 2023). Geophysical models help to characterize the recharge pathways through subsurface resistivity translation into insights on water flow and storage potential (Gong et al., 2023). Appropriate protection and management are therefore necessary for sustainable groundwater resources (Aderemi et al., 2022; Luo et al., 2020).

Geophysical models offer non-invasive techniques for groundwater recharge estimation by assessing subsurface properties that affect water movement and recharge. Techniques such as Electrical Resistivity Tomography (ERT), Ground Penetration Radar (GPR), and Electromagnetic (EM) surveys detect soil moisture, lithological boundaries, and aquifer structures. Furthermore, these models infer spatiotemporal permeability, porosity, and saturation levels and offer crucial insights to recharge pathways. Different configurations, array types, investigation depths, and promising factors which influence geophysical methods performance. With the ever-present climate change problem affecting the water resources that humans rely on daily; it is paramount to take inventory of the tools at our disposal to monitor and find this precious resource. While literature on geophysical methods exists, there is still a scoping review to assess the trends within published literature on groundwater and geophysical methods. This review explores the emerging trends and global synthesis of research using ERT, EM and GPR approaches for recharge estimation and delineating recharge zones with the objectives to critically analyze the capabilities, limitations, trends and integration potential of these methods across diverse hydrogeological settings. Highlighting the methodological trends, case studies application, limitations and future research gaps, this scoping review provides the non-invasive and indirect approaches for groundwater monitoring under changing climate and diverse land use.

2 Materials and methods

This review employed systematic and scoping approach identify, evaluate and synthesize global research perspective on Geophysical methods like Electrical Resistivity Tomography (ERT), Electromagnetic (EM) survey and Ground Penetration Radar (GPR) for used groundwater recharge estimation.

2.1 Literature search strategy

A comprehensive literature search was conducted using Web of Science (WoS) database covering all the publications utilizing ERT, EM and GPR for groundwater recharge study. The keywords and combinations used for search were "groundwater recharge," "electrical resistivity tomography" or "ERT," "electromagnetic survey" or "EM methods," "ground penetration radar" or "GPR," "geophysical methods" and "recharge estimation" to get the relevant literature. PRISMA search strategy (Figure 1) guidelines were adopted for the literature search and selection process which provided a standardized approach for systematic and scoping review analyses.

2.2 Inclusion and exclusion criteria

After the literature search, all the papers were screened and included based on criteria. The criteria used was that the papers which focused on geophysical methods in estimating or identifying recharge, published in peer reviewed journals, conference or academic reports which provide the case study data, methodology description and result synthesis related to recharge estimation. The PRISMA diagram lays out the steps utilized in narrowing down the articles selected for review in a non-biased manner. Non-articles were removed from the records due to the lack of review associated with other forms of scientific media. Finally, words such as "airborne, cavities, caves," and "slopes" were also used to screen the geophysical literature sources. Proceedings. Furthermore, articles were excluded which contained "cavities, caves, and slopes." Once the screening phase reduced the number of articles down to a sample size of 93 total surveys, manual cataloging and screening of each article was conducted. Each type of survey, following the same step-by-step filtering and screening, yielded a different number of articles. While this is consistent with other PRISMA analysis in other fields, this poses a fundamental problem when examining the frequency of trends within the data. There were no even distributions between the number of studies selected for analysis, and this certainly affected the trend graphics displayed in other sections of this study.

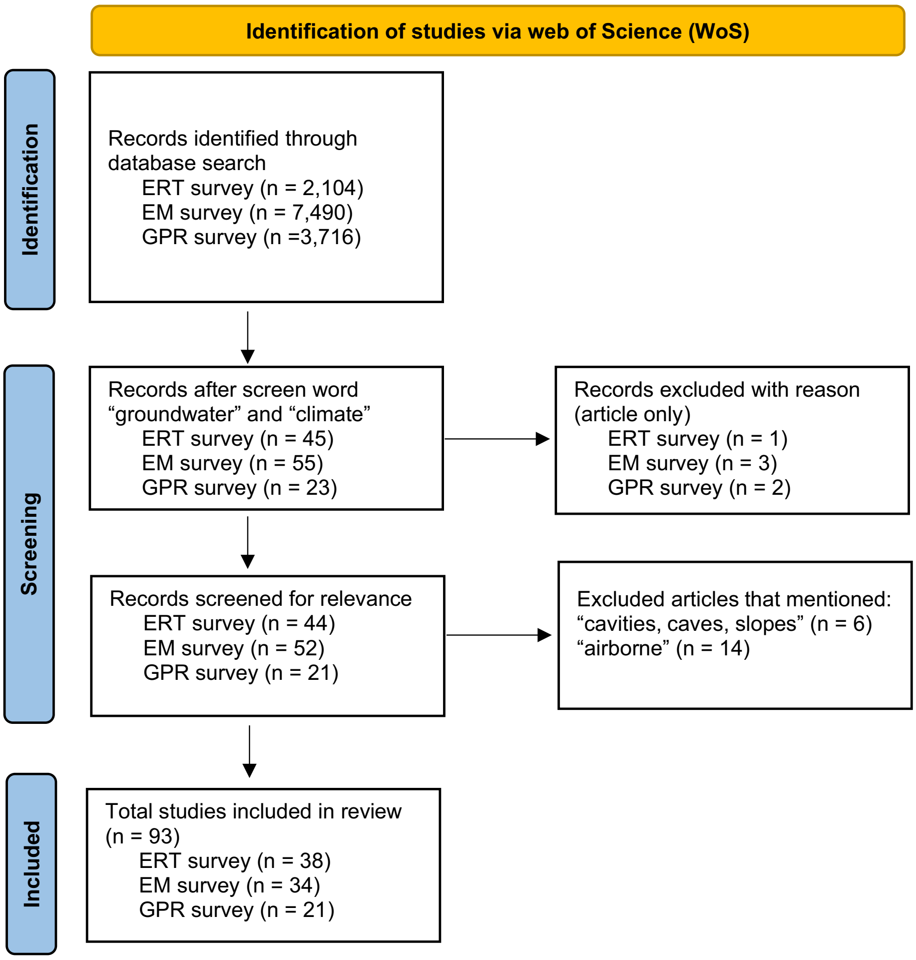

FIGURE 1
PRISMA search strategy illustrating identification, screening, eligibility and inclusion process of reviewed studies on geophysical methods (ERT, EM, and GPR) for groundwater recharge estimation.

2.3 Data extraction and classification

The selected literature after screening were extracted for detailed analysis using geophysical method, geographical location of the study, publication year, climate of the area, hydrogeological setting, configuration type and statistical metrics. An overview of the three geophysical methods and comparisons was also employed based on equipment, survey type, electric configuration, penetration depth, measurement method, range, resolution, data acquisition with pros and cons were summarized. Furthermore, yearly trends, geographical distribution, climatic analysis and the factors influencing groundwater recharge estimation through geophysical survey methods are summarized in detail.

3 Results and discussion

3.1 Scale of the study

Using the publication database “Web of Science,” the study featured the examination of publications per geophysical method. This includes 38 ERT survey publications, 34 EM publications, and 21 GPR publications. Using the PRISMA method for screening and selection, 93 published journal articles featuring geophysical surveys were recorded. The search words queried included “groundwater” and then the name of the survey. The top relevant articles that appeared were examined for each of the methods. The year of publication, the country where the study site resided, the climate of the study area, and key terms were cataloged for analysis. The analysis involved the creation of word clouds to visualize the frequency of items within the papers for bulk comparison. Graphics and trends were examined and thoroughly investigated to provide possible insight into why the observed trends were seen. A detailed overview and comparison of the geophysical method used in this systematic and scoping review is also discussed.

3.2 Overview of geophysical survey tools

While many geophysical surveying methods exist today, it would not be a comprehensive scoping review of geophysical methods without mentioning the merits of the seismic surveying of the 1900s that allowed for future geophysical work to be conducted. German scientist Ludger Mintrop (1880–1956) is often credited with the invention of seismic testing that involved striking the ground to measure seismic refraction patterns for salt dome and oil exploration (Bednar, 2005). This work involved measuring the relationships of different waves as they attenuate through the subsurface. Mintrop's work is the predecessor of the seismic refraction surveys that are conducted today with dynamite or by dropping weight on a steel plate to measure P and S waves as they refract through various layers of lithologies in the subsurface. This scoping review is primarily concerned with groundwater investigation. Furthermore, the identification of saturated or semi-saturated layers using seismic surveying is difficult due to the wide range of possible reflection velocities that register when conducting this type of survey (Grelle and Guadagno, 2009). For these reasons, seismic geophysical surveying was omitted from the search query list. Other geophysical methods show much more promise at imaging the subsurface for highly saturated areas. The three geophysical methods that will be examined in this scoping review are the following: ERT, EM, GPR surveys. These three methods will be compared in this review and Table 1 shows a summary of each method.

3.2.1 Electrical resistivity tomography (ERT)

ERT, in its infancy started in the 1940s by scientist Andrei Tikonov by utilizing electrical resistive properties in looking for highly conductive copper deposits in the Soviet Union (Rezgui, 2018). A relation between a transmitter emitting electrical signals and equally spaced electrodes in the ground to measure the change in voltage across an array of electrodes (often 4) became common place for imaging subsurface resistivity. An ERT survey is a geophysical method of collecting data from sending an electrical current from a transmitter to electrodes in an array. While many methods persist for array set ups, among them the Schlumberger array is considered the best for groundwater aquifer imaging but still the optimal electrode configuration depends on local geological characteristics (Urruela et al., 2021). This array type consists of four electrodes, with a transmitter sending out controlled electrical signals and a receiver collecting the disputed signals that interact with the earth subsurface. The resistance of the material on earth is a derivation of Ohms law. Equation 1 is the resistance of the materials between the electrodes:

$$R = \frac{V}{I} \tag{1}$$

Once this is done, apparent resistivity (Equation 2) is calculated:

$$p_a = K \times R \tag{2}$$

The geometric factor K can be derived in Equation 3:

$$K = \frac{2\pi a}{n} \tag{3}$$

where, R is resistivity (ohms), V is voltage (volts), and I is current (amperes) (Hussein et al., 2023). p_a is the apparent resistivity in ohm meters, K is the geometric factor in meters and R is resistivity in ohms,

TABLE 1 Comparisons of geophysical methods [electrical resistivity tomography (ERT), electromagnetic (EM), and electromagnetic (EM)] surveys for groundwater recharge estimation.

Parameters	Geophysical survey methods		
	Electrical resistivity tomography (ERT)	Electromagnetic (EM) survey	Ground penetration radar (GPR)
Description	Electricity is sent into the ground to create a map of resistivities.	Change in induced magnetic field that relates to subsurface lithologies.	A radar pulse is sent into the subsurface and reflective return times are converted to determine subsurface materials.
Equipment	Shallow electrodes in arrays, electrical transmitter and receiver	Electromagnetic with magnetic field transmitter and receiver	Radar wave transmitter and receiver, clock mechanism
Survey type	2D, 3D and time lapse ERT	Time-domain and frequency-domain EM	Continuous all profile, cross-line, point measurement
Electronic configuration/ Frequency range	Wenner, Schlumberger, dipole–dipole	Shallow (high frequency) and deep (low frequency)	15–3 Ghz
Penetration depth	Shallow vs. deep (based on electrodes spacings)	High frequency for shallow and low frequency for deep	Up to 30 meters in sandy soil while lower in clay and saline soils
Measurement method	Resistance	Conductance	Rippled 2D image of reflection
Range	10–5,000 ohm-m	0.5–300 mS/m	Dielectric permittivity
Resolution	High at surface and decreases with depth	Conductive zones (high) and resistive zones (low)	High at surface and decreases with depth
Data acquisition method	Multiple electrodes and static setup	Mobile or static	Static GPR profiling or continuous
Application	Recharge, aquifer delineation, plume mapping	Groundwater detection, contaminants and salinity	Shallow groundwater mapping, soil moisture and fractures
Pros	Deep investigation, different array type	Faster	Wheeled system reducers time to capture area, operated by one individual
Cons	Time-consuming set up and operation. Larger margins for error with many electrodes.	Major distortion occurs with electrical sources like powerlines, buried wires, and magnetic or metallic subsurface lithologies.	Poor resolution past 1 meter. Best for finding items rather than broad analysis.
References	Hussein et al. (2023) and Urruela et al. (2021)	Rauf et al. (2019) and Wheeler and Cheadle (2014)	Bednar (2005) and Poluha et al. (2017)

a is the spacing between adjacent electrodes in meters, n is the amount of electrode spacings (number).

Electrical resistivity surveys have been continuously used for decades in areas such as mineral exploration and subterranean pollution sites (Greenwood and Buth, 2017). The ability to track resistive fluids in the ground using an ERT survey has many applications in the civil engineering realm as well as geoscience consulting for construction projects. This paper aims to highlight this technology's use in groundwater surveying and exploration. Recent studies have shown the ability to image highly conductive seawater intrusions in coastal aquifers using ERT technology. This involves mapping coastal aquifers along the Mediterranean in Italy and Greece to measure the extent of saltwater intrusion into freshwater aquifers that supply vibrant coastal cities with water resources. Other studies including one conducted on the Munijhara watershed in India, are able to estimate groundwater recharge by taking multiple readings over a given time to see how the annual recharge of the aquifer changes with precipitation fluctuations (Sethi et al., 2009). The usages of ERT for aquifers are also noted as being used to identify likely water saturated zones within arid climates. This can be especially useful when the water resources of the area is limited. An example of this occurred in a 2011 study in Sudan to map likely saturated sandstone aquifers in the Nuban Mountains for possible well drilling sites. The ERT survey identified zones 10 meter below the subsurface that contained resistivities anomalies consistent with a saturated sandstone layer (Mohamed et al., 2011). Electrical resistivity tomography allows groundwater exploration and aquifer mapping. Based on the 93 papers reviewed in this scoping review on groundwater and ERT surveying, there can be no doubt that this method is effective at identifying and mapping groundwater resources and lithological structures that lie beneath the earth's surface.

With respect to agriculture, ERT possesses many ways of improving water use efficiency. ERT soil characterization mapping has been conducted on areas with compacted soil for root formation factors. ERT can be utilized to measure aquifer saturation levels on wells drawing for crop production irrigation (Watlet et al., 2018). Other studies discuss the ability for ERT to be a promising method for understanding soil organic content monitoring (Turki et al., 2019). Using geophysical methods on irrigated crop land provides invaluable information for growers to understand the aquifer beneath. More research is needed to understand the dynamics that control aquifer saturation levels, however using geophysical methods such as ERT is a first step towards more efficient water usage in agriculture.

3.2.2 Electromagnetic surveying (EM)

Electromagnetic (EM) surveying involves generating a magnetic field via an alternating electrical current, which creates a primary magnetic field. This field propagates through the ground from the transmitter. As the primary field interacts with subsurface materials, it induces a secondary magnetic field. The receiver measures strengths and phases of this secondary field (McLachlan et al., 2021). The frequency of the alternating current of the electromagnet is how the depth of investigation is adjusted. At higher frequencies, more of the field is dissipated quicker and, therefore, is good for mapping shallow units. At lower frequencies, the field penetrates deeper into the earth at lower energy provides a deeper scan of the subsurface. The trade-off is that the lower energy weakens the strength of the magnetic field of the secondary field, consequently lowering the resolution of the readings (Wheeler and Cheadle, 2014). The output of the system is a conductivity map that shows the ease at which a magnetic field attenuates throughout the subsurface.

Similarly to the ERT survey, a map of resistance can be generated from the EM survey. This is due to the fact that resistivity and conductivity are inverses of each other. Within Equation 4, δ, the skin depth, in meters, is calculated. The skin depth represents the distance at which the amplitude of the primary electromagnetic field decreases to approximately 37% of its surface value, and it is influenced by the frequency and conductivity of the subsurface materials:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{4}$$

where ω is the angular frequency (radians per second) of the electromagnetic field, μ is the magnetic permeability of the material (which is generally assumed to be the permeability of free space) with units of Henries per meter, and σ is the electrical conductivity of the material in units of Siemens per meter (Rauf et al., 2019). The primary magnetic field penetrates the ground and induces eddy currents into subsurface features. These eddy currents then create their own electromagnetic field, which is recorded with a receiver. Similar to ERT, the accumulation of various secondary electromagnetic fields can be used in an inversion model to calculate the depths of various subsurface features. The main benefit of an electromagnetic survey is the speed at which the data can be collected. There is no direct contact with the ground, therefore, various methods are employed to gather bulk accurate electromagnetic conductance maps of areas. Methods include using an aerial system, a pulled hitched system by an off-roading vehicle, or even two-person teams carrying the transmitter and the receiver at set distances and marking out an array pattern to generate 2D resistivity maps of areas. Drawbacks of the EM survey include its reactivity to external electrical sources. This means powerlines, buried cables, and magnetic minerals are all things that can distort the data to give false readings (Zhdanov, 2010). The EM survey does not contact the ground directly, therefore factors that influence the invisible magnetic field within the area are very important.

3.2.3 Ground penetration radar (GPR)

Ground penetrating radar (GPR) surveys involve emitting a radar pulse into the subsurface. This pulse is emitted by a transmitter and ranges from 900 MHz-1GHz (Benedetto and Benedetto, 2014). This pulse spreads through the ground and then reflects off various structures and subsurface features. The reflected radar signal then travels back to the receiver. This time difference in arrival times of radar signals allows for the calculation of layered lithologies as radar waves attenuate differently in different surfaces depending on factors such as porosity, fluid presence and mineral structure of the layers. Equations 5, 6 depict how the depth is calculated using ground penetrating radar:

$$V = \frac{c}{\sqrt{\varepsilon_r}} \tag{5}$$

$$z = \frac{vt}{2} \tag{6}$$

where, V is the velocity of the electromagnetic wave (m/s), c is the velocity of electromagnetic velocity in a vacuum (m/s), ε_r is the dielectric constant (unitless). Z is the depth of the target reading (m), and t is the two-way travel time (s) to a subsurface reflector (Poluha et al., 2017).

This technology has been around since 1910 when German geophysicists used continuous radar waves to measure changes in reflection time as the ground beneath them changed (Bednar, 2005). Fast forward to today, there is various types of GPR machines and uses for this technology. This survey must have direct contact with the ground to send these radar waves into the subsurface, however nothing is directly drilled into the ground. This allows for the most practical method of GPR surveying using a wheeled system to create an array of fields. Unlike EM or ERT surveys however, there will be no resistivity map generated. The output of this system is a rippled diffusion pattern that can be used to identify structures within the subsurface. The most common application of this technology is used in smaller settings of depths of 1–10 meters. The reason for this is the strength to generate such a radar blast, which often requires a larger system, and the resolution decreases with depth as the waves attenuate through the layers. Therefore, the near-surface structures are much more defined and known when conducting a GPR survey.

GPR is the most versatile tool that has been used for mine detection, civil engineering projects, and soil moisture penetration (Benedetto et al., 2015). The arrival times of the reflecting waves allow for filtered parameters to be in place to screen any excess noise depending on the project and the depth of investigation needed. Often, the largest downside seen with GPR is the interpretation of and "aperture of radar distortion" seen when waves hit a buried object. The description and interpretation of the object only come as a function of time, and these reflected arrival times must be interpreted to understand the layers/objects that are buried. The effects of the propagation of radar waves on different bodies are also different. The angle at which radar waves attenuate must also be considered when measuring subsurface structures, as angle of the incident radar wave compared to the angle of reflection from the target area is different and can lead to problems with interpreting the shape and size of the structure (Benedetto and Benedetto, 2014).

3.3 Trend analysis

Upon review of the three geophysical methods for investigating groundwater and recharge, trends exist within the publication keywords. These are words that the authors deemed key to adequately describe their paper. After examination of all the keywords of all the 93 articles reviewed, several trends emerged (Figure 2). The term "inversion" appeared 11 unique times within key terms across the sample, suggesting that the studies conducted required data manipulation and additional computer model inversions. Many models (2D or 3D) require an inversion of the 1D raw data to create final figures. An example is depth to replace frequency on the 1D models of EM surveys to create a conductance vs. depth graphic that is more understandable to the community (McLachlan et al., 2021). The term "coastal" appeared 12 unique times to suggest that coastal aquifers and groundwater are of particular importance to the public as seawater intrusions pose a threat to coastal aquifers (Klassen and Allen, 2017). It should be noted that the word "intrusion" was observed 9 times within the keywords analysis. In addition, coastal areas typically experience a higher population density compared to their water resources; therefore, one can reasonably infer that groundwater surveying in these areas would be important (Boretti and Rosa, 2019). The term "hydrogeology" appears 8 unique times and demonstrates the importance of understanding the aquifer content and recharge rates and how important a comprehensive understanding of the local geology is to these studies.

Other trends observed involve the years published and the location of said studies. Groundwater exploration surveys suggest an apparent stress on the water supply or a lack of understanding of subsurface aquifers. Thus, it can be inferred that areas that experience heavy groundwater usage or lack of plentiful, easily accessible water resources are more likely to conduct a study. This can be directly observed when examining the climate of the study areas. The climates of each of the study areas of each survey publication were noted and archived to examine trends. Unsurprisingly, a frequent climate survey was "arid" in 16 unique publications. This points to arid regions receiving little rainfall and often having water-stressed resources. The issue of water scarcity in arid regions is exacerbated by the effects of global climate change (Morante-Carballo et al., 2022). The other popular terms were tropical (7) and subtropical (19). Two explanations exist for this trend. The first is that the majority of the tropical and subtropical areas surveyed lie within Africa or the Indian subcontinent. African regions are more susceptible to water resource issues, and thus, more exploration and understanding of where water is located within Africa is of public importance and increases the likelihood of geophysical research. Studies that fall under tropical and subtropical within India can be attributed to the topography of the Himalayas and the remoteness of the study areas. Isolated villages and towns within India often deal with unique geographical and mountainous terrain that makes water infrastructure difficult (Bathla, 1999). This would explain the need for groundwater surveys to sustain the largest populated country in the world.

Over the past few decades geophysical methods are gaining attention due to their potential to non-invasive and indirect characterization of subsurface hydrological processes, especially for groundwater recharge estimation. Understanding the historical development and progression of geophysical methods is essential for groundwater resources research. Highlighting the development of those methods, a literature search from Web of Science revealed that earliest application of EM appeared in 1981, followed by GPR in 1990 and ERT in 1992. Figure 3 illustrates the growing interest in geophysical mapping for groundwater. The trend is increasing yearly, with 2022 being an exception due to the COVID-19 pandemic. There

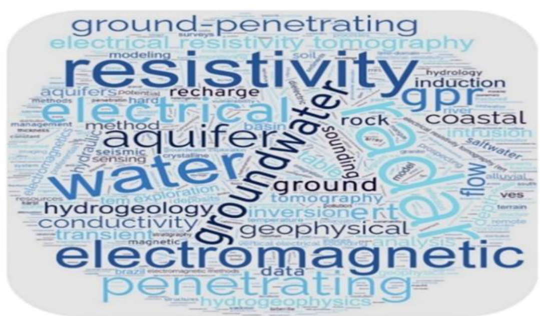

FIGURE 2
Word cloud of key terms from 93 recorded publications.

is enough evidence to support the notion that surveys will continue to be useful in mapping and identifying aquifers around the globe. An examination of the publication number trends was also considered. The yearly publication trends can be explained for EM and GPR, which are often cheaper methods of geophysical mapping. While the equipment prices of all three methods are a substantial investment, ERT, until recently, has been extremely expensive. This also deals with the fact that the depth of investigation of ERT is directly proportional to the length of cable spacing. Moreover, the more cables are needed, the larger the cost of the system. This creates an economic barrier to entry in terms of ERT for groundwater investigation. ERT begins to accelerate to become the dominant groundwater survey tool in 2021 for maximum publications across all years. The number of surveys conducted also trends upward in all types, indicating that all three methods provide viable means for groundwater exploration given the study area. The increase in groundwater surveys can be linked to global climate change affecting water resources. The change in temperatures, precipitation, and growing global populations continue to put the water supply of the world under strain (Al Atawneh et al., 2021). Most geohydrological models indicate that groundwater recharge is depleting across many regions. This could provide an explanation for the increase in groundwater recharge mapping and aquifer monitoring using geophysical surveying.

3.4 Survey geographical distribution

The map compiled in Figure 4 highlights the number of geophysical groundwater papers published by each country. It should be immediately noticeable that the three countries with the three largest populations on earth are the top three leading countries publishing groundwater geophysical surveys. The U.S. (14), India (7), and China (4) are the three largest countries in the world in terms of population. Population and demand for groundwater are directly related, as water is the most important source for living things (Boretti and Rosa, 2019). The cost of the survey equipment should be noted as well. The high cost of these mapping tools reflects on the countries that use them with U.S., China, Germany, England, Canada, India, Italy and Brazil representing 8 of the top ten highest GDP's in the world. In correlation, each of the countries listed above has published at least 2 or more geophysical surveys on groundwater. The data collected from this scoping review supports the correlation that countries with higher GDP publish more research (National Science Board, 2021).

It should be noted that most U.S. surveys were conducted in arid or water-stressed areas. The effect of global climate change is altering traditional weather patterns and affecting groundwater resources. So, while the whole country might be highlighted in the map above, the areas within the countries where the surveys are taking place are likely an area where water resources in a region where water is stressed or will become stressed in the future. The map is a visual representation of the amount of geophysical groundwater surveys being conducted around the globe. The analysis also shows the wide extent of groundwater geophysical surveying. While no analysis was done on the preferential types used in various areas, the map above serves as a testament to the fact that groundwater geophysical surveying for resource mapping can be applicable to practically all corners of the globe.

3.5 Climate distribution analysis

A review of the climates in which geophysical surveys on groundwater were conducted yielded the following bar graph shown in Figure 5. Figure 5 perhaps demonstrates the most poignant point of all; groundwater estimation and mapping are important in all climates. The effects of global climate change are directly impacting the rates of recharge and precipitation on a global scale (Davamani et al., 2023). The presence of groundwater surveys across all the biomes on the planet indicates that no region is more stable than others due to sub-surface processes not being fully understood. Granted, arid and mountainous climates appear in bulk due to their

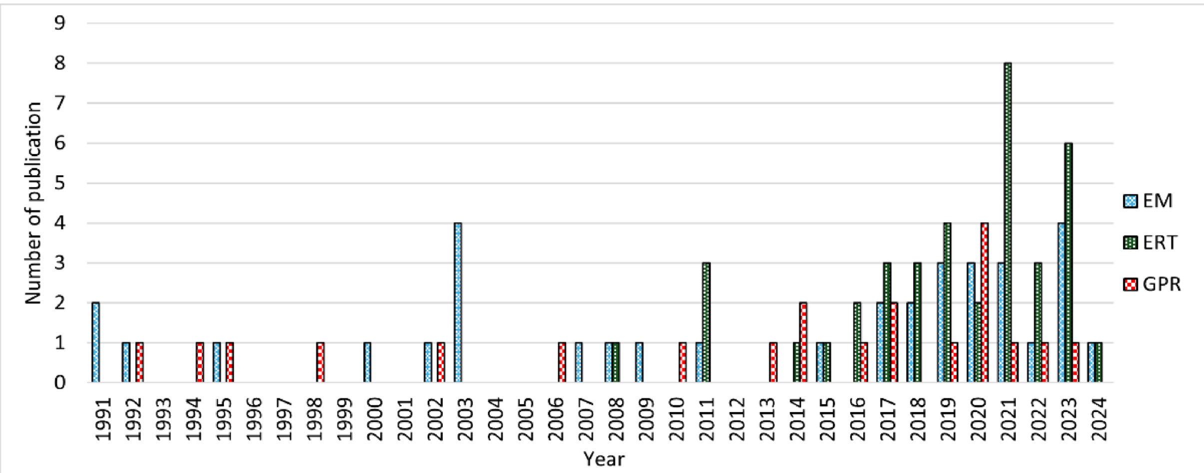

FIGURE 3
Temporal distribution of published studies using *electrical resistivity tomog*raphy (ERT), electromagnetic (EM) methods, and ground penetrating radar (GPR) for groundwater recharge estimation. The figure illustrates the growth in scientific attention to each method over time and helps visualize methodological trends and adoption patterns across global case studies.

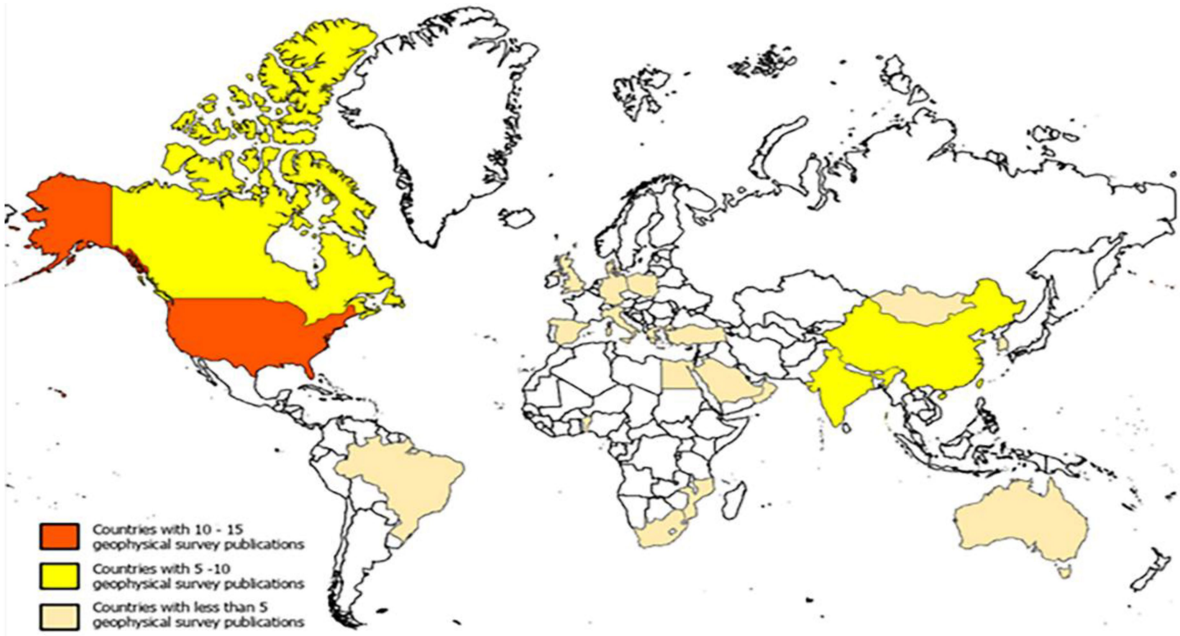

FIGURE 4
World map of geophysical survey sites from selected publications.

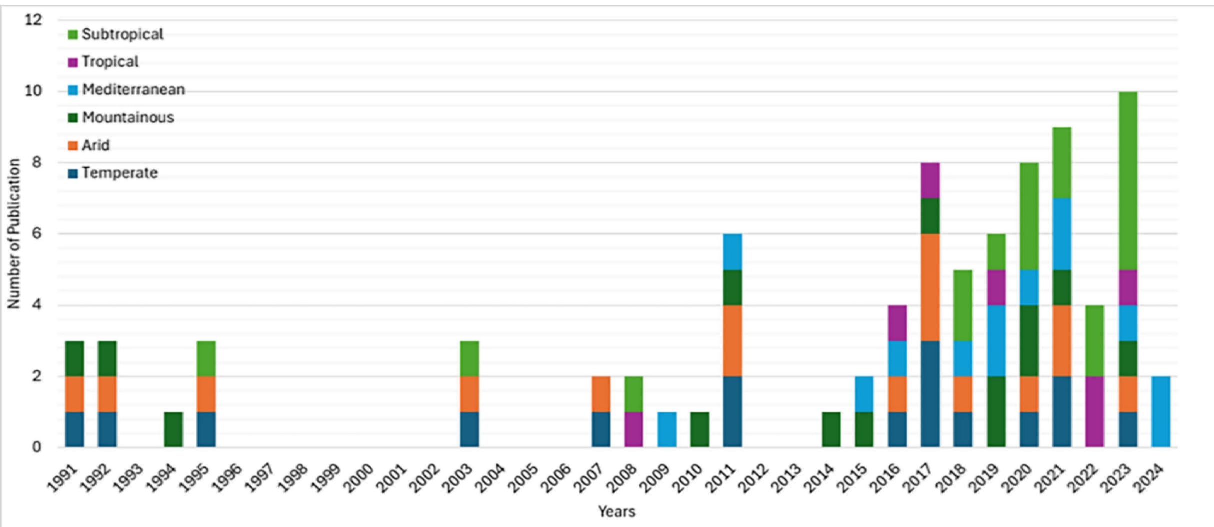

FIGURE 5
Yearly trends identified by climate of the survey site represented in selected papers.

natural disposition to water resources, but temperate and subtropical climates are also equal targets of these groundwater surveys. In fact, temperate climates have seen the most geophysical groundwater surveys while tropical climates see the least.

Upon review, there are differences between the climate areas studied for the survey sites. The tropical biome experiences the lowest amount of geophysical groundwater surveys. The likely explanation for this trend is the fact that tropical climates receive the most rainfall of any of the other biomes. This increase in rainwater leads to more surface water likely used to supply population centers and less water stress on humans living in these areas (Konapala et al., 2020). Moving forward, the impacts of global climate change are likely to cause an increase in groundwater surveys in the subtropical zones. The slow conversion of subtropical lands into arid environments is well documented, with the Sahara Desert increasing in size by 10 percent in the last 100 years and growing with the shifting of rainfall patterns. The lands that once were subtropical surrounding the desert are becoming more arid due to the effects of climate change (Thomas and Nigam, 2018).

The same trends are observed in Mediterranean climate data. Mediterranean climate encompasses a small geographical area, yet there is a high population density due to the desirable climate and economic opportunities. This small, unique climate has seen and will continue significant desertification due to climate change and, therefore, lends itself to explaining the significant increase in groundwater surveying (Lionello et al., 2014). As the Mediterranean climate continues to convert to arid, the large population centers will continue to seek out groundwater resources. The effect of this is also worsened by all Mediterranean climates being located next to saltwater bodies. Coastal aquifers are known to face issues with saltwater intrusions, rendering them ineffective for drinking water once contaminated with salt (Klassen and Allen, 2017). This would be an added incentive for researchers or academics to conduct geophysical groundwater surveys in the Mediterranean climate zone atop the aforementioned.

The temperate climate zone is described by four distinct seasons with varied precipitation. Much of the world lives within a temperate climate zone. The temperate climate zone features the bulk of all agricultural operations in the world. This makes temperate groundwater for human consumption and irrigation for crops important to a sustainable economy (Dornik et al., 2024). This climate zone also saw the most geophysical surveys. This was unexpected in the findings as we assumed that these areas maintained a large amount of water resources from surface water or their precipitation. The reason for large amounts of groundwater geophysical surveying perhaps lies in the motivation trends behind the papers than with climate alone but also population growth and demands are the promising factors.

The 16 arid geophysical surveys concern themselves with the words of "exploration" and "resource identification." This mainly owes to the notion that semi-arid and arid environments receive less rainfall and maintain lower levels of surface water resources. These features are certainly exacerbated by the onset of global climate change, and therefore, these surveys are more concerned with identifying areas of water saturation in the subsurface. Other studies in the temperate climate category appear more concerned with the "quantification of groundwater resources" or "identifying aquifer size and health." This difference likely occurs from the shift in priorities with arid regions concerned with finding more water and temperate regions concerned with the management of known water resources (Wiederhold et al., 2021). These surveys are an attempt to visualize the hydrogeological features under the surface and study how they are changing with time in respect to climate change. The reasoning and factors behind groundwater geophysical surveying are numerous, however, observing the trends has led to the above theories as to why the trends presented were observed.

3.6 Integrated analysis of geophysical methods and influencing factors

Detailed analysis of the data extracted from the selected papers illustrates different configurations, array types, investigation depths, and the promising factors which influence geophysical methods performance. The statistical metrics and configurations used for survey methods are shown in Table 2, which indicates the overall low

TABLE 2 Statistical metrics and configuration of the geophysical surveys used in the selected literature for groundwater recharge estimation.

Survey name	Configuration/array type	Statistical metrics		Reference
		RMS	L2	
ERT	Wenner array electrode	2.73	0.83	Redhaounia et al. (2016)
ERT	Gradient array and pole-dipole array	5		Azffri et al. (2022)
ERT	Not specified	0.69		Moulds et al. (2023)
ERT	Wenner-Schlumberg, 64 electrodes	Generally, <3.4%, most being under 2%		Ayari et al. (2023)
ERT	Pole-dipole and dipole–dipole	12.7 and 6.2% for Location 1; 15.3%		Gyeltshen et al. (2020)
ERT	Pole-dipole and pole-pole	Ranged from 0.014–0.302 for sinkhole cavity, 0.023–0.388 for vein-type		Park et al. (2018)
TEM and Magneto-ERT (MERT)	Dipole–dipole 2D ERT	7.7% for 2-D inversion, 9.4% for forward model		Ardali et al. (2018)
ERT	Wenner and dipole–dipole	5–10%	0.2–0.4	Mohamed et al. (2011)
EM	DUALEM-2 system	12.5 to 22.0 cm for field 1 and 11.2 to 22.1 cm for field 2		Farooque et al. (2020)
EM	Wenner array, 4-electrode system for field measurements	<5%	0.2	Robinson et al. (2005)
TEM	2D TEM (transient electromagnetic profiling)	2.96		Lévesque et al. (2021)
ERT	Electrical resistivity tomography (ERT) conducted with lines S1, S4, E4, R4, E7, etc. to analyze subsurface structure and resistivity	Between 1.4 ms to 4.5 ms for different ERT and seismic models		Christensen et al. (2020)
EM	1D TDEM (Time Domain Electromagnetic Method) inversion followed by a 2D resistivity cross-section for interpretation. The survey included 9 TDEM stations along seismic line GI-0082	Final TDEM interpretation was reduced from 3% to slightly more than 2%		Shtivelman and Goldman (2000)
TEM	Fixed-loop array with 3D coil	High RMS but NS		Realpe Campaña et al. (2017)
Multi-methods	Vertical Electric Sounding (VES), Transient Electromagnetic (TEM), Audio-Magnetotelluric (AMT), Control-source Magnetotelluric (CSAMT), Very Low Frequency (VLF)	1.4 for profile 1; 2.3 for profile 2		Abdel Zaher et al. (2021)

Root Mean Square (RMS; <5%) and low L2 norm (Euclidean norm) for diverse configurations reflect accuracy with best fitness. The geological setting affects the performance and choice of the geophysical method to use. Table 3 shows the distribution of the geophysical survey method based on geological settings and soil types. ERT ranked first based on the geological setting used in a diverse range of soil, followed by EM and then GPR (comparatively less literature for ground water recharge estimation). Depth of investigation (DOI) is also an important factor for considering the geophysical method selection for investigation. Figure 6 presents the investigation depth (m) across geophysical methods with array types. Figure 6 showed that maximum investigation depth was noted for EM followed by ERT and GPR. The configuration or array type used in the selected research is plotted against the number of papers (Figure 7). Overall, the 2D ERT configuration was found to be the maximum followed by pole-dipole and dipole–dipole, VES, TDEM and Wenner array. Various environmental and subsurface factors complicate the data and interpretation of the geophysical methods. Details of the factors and their characteristics affecting the geophysical survey methods are presented in Table 4. Among the factors, subsurface heterogeneity and high material conductivity often reduce resolution and distort signals, influencing all methods in conductive soils. ERT and EM measurements are affected by salinity and saturation. The GPR signals are attenuated in saturated and saline conditions. Data quality is affected by poor electrode-ground contact topography and cultural noise. Seasonal variability and frequency-depth trade-offs affect the resolution and accuracy of the survey. The effectiveness and repeatability of the geophysical survey methods are influenced by weather conditions and water table depth. Considering these factors, an adaptable and well-planned geophysical survey method selection in diverse geological settings can enhance the precision of groundwater recharge estimation.

3.7 Limitations reported in existing literature

Besides the critical insights into geophysical models for groundwater recharge estimations, the limitations reported in the included literature are summarized. Among the limitations of the geophysical methods, studies reported that depth and resolution affect the survey performance. ERT is limited to shallow depths (up to 50 m), which restricts deep subsurface exploration, and additional techniques like jump in magnetic potential and magnetic data are needed to assess the deeper investigations (Gao et al., 2018). GPR penetration is limited (1–3 m) assuming uniform resistivity thereby affecting precision (Albuquerque et al., 2022; Mesbah et al., 2017). In TEM and ERT, the limited vertical resolution affects the small-scale variations (Christensen et al., 2020; Ronczka et al., 2015). The potential inaccuracies due to variations in vertical resolution and characteristics are reported while merging SSR and GPR datasets (Cardimona et al., 1998; Mohammadi Vizheh et al., 2020). Data quality and environmental influence are also reported to influence recharge estimation through geophysical models. Environmental factors such as salinity, soil heterogeneity, and other instrumental errors (noise and

TABLE 3 Geophysical methods (ERT, EM, and GPR) used in selected papers for different geological settings and soil types.

Geological setting/soil type	Geophysical survey methods		
	Electrical resistivity tomography (ERT)	Electromagnetic (EM) survey	Ground penetration radar (GPR)
Karst, limestone, dolostone	✓		
Alluvial soils and floodplains	✓		
Sandy and coastal soil	✓	✓	✓
Mixed sandy and clay soils	✓		
Quaternary sediments, Moraine, Talus, fractured bedrock	✓	✓	
Clay rich soil and aquitards		✓	
Weathered and fractured basement rocks	✓	✓	
Granite and crystalline basement	✓	✓	
Coastal dunes and sand formations	✓		✓
Sedimentary basins and oil reservoirs	✓	✓	
Lagoon-contaminated and saline intrusion	✓	✓	
Complex weather layering and fault zone	✓	✓	
Silty loam, silt and peats		✓	✓
Anthrosol, technosol and marl rocks		✓	
Unconsolidated Sandy formation	✓	✓	
Eolian sand dunes and deserts soil	✓	✓	
Fractured aquifers and dolomites	✓	✓	

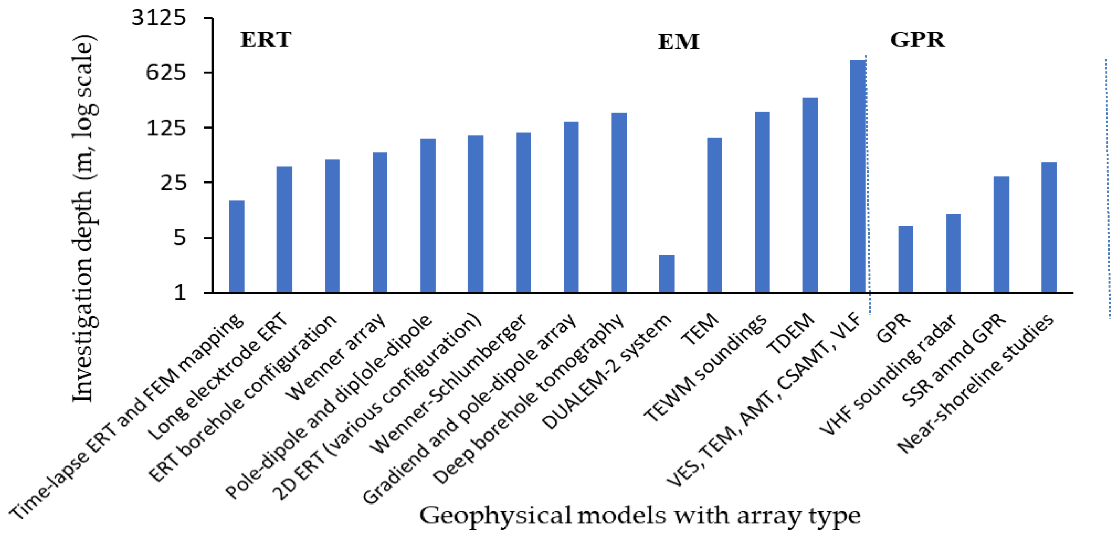

FIGURE 6
Investigation depth (m) for ERT, EM and GPR with configuration/array type used in the included literature. Where, DUALEM (Dual-Axis Electromagnetic), TEM (Transient Electromagnetic), TEWM (Time-Domain Electromagnetic Waveform Method), VES (Vertical Electrical Sounding), AMT (Audio-Magnetotelluric), CSMAT (Controlled Source Audio-Magnetotelluric), VLF (Very Low Frequency), VHF (Very High Frequency) and SSR (Seismic Surface Refraction).

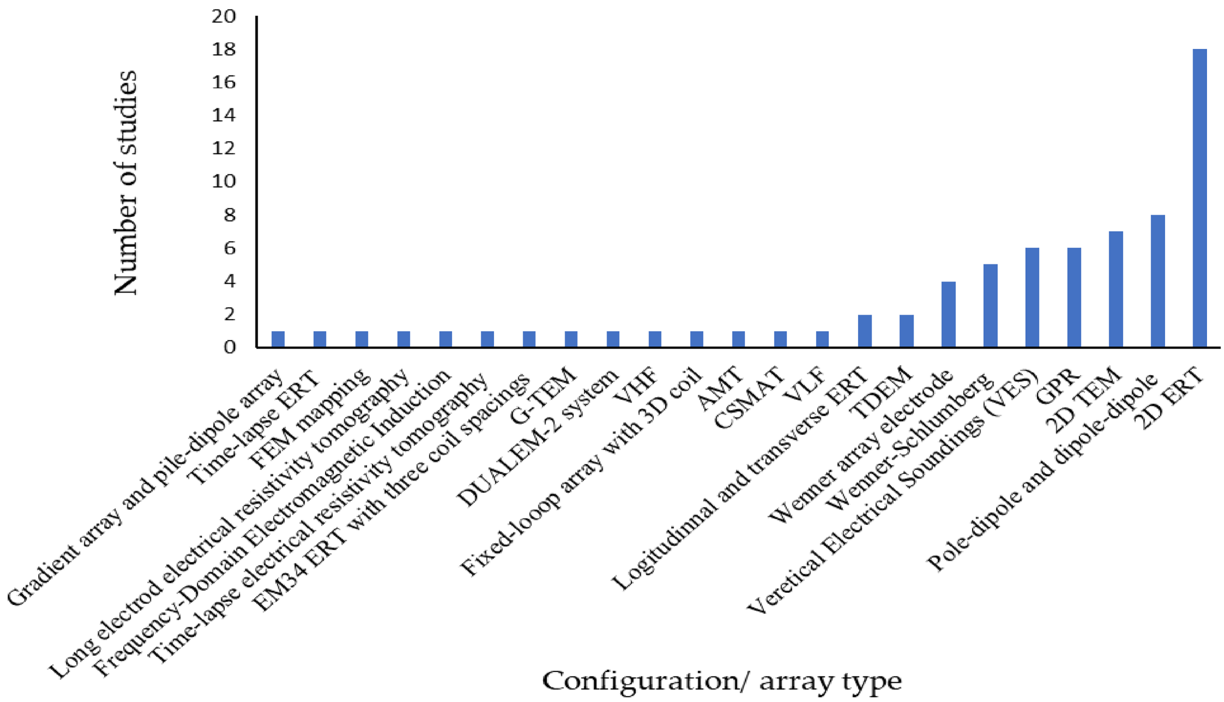

FIGURE 7
Configuration/array type of geophysical methods used in the included literature. Where, DUALEM (Dual-Axis Electromagnetic), TEM (Transient Electromagnetic), TDEM (Time-Domain Electromagnetic Waveform Method), VES (Vertical Electrical Sounding), AMT (Audio-Magnetotelluric), CSMAT (Controlled Source Audio-Magnetotelluric), VLF (Very Low Frequency) and VHF (Very High Frequency).

system failure) lead to inaccuracy (Busato et al., 2019; Heggy et al., 2023). Surface conditions and electrode spacing also affect the geological results (Andrade, 2011; Singh and Tripura, 2023). Jiang et al. (2020) reported geometric issues in 2D and MRT assumptions in the vadose zone leading to artifacts. Methods integration and modeling are reported to be used for more accurate results (Ma et al., 2024). Zhang et al. (2021) stated that non-uniqueness and interpolation techniques limitations of models leads to uncertainty in resistivity. Terrian and seasonal variability are also reported by De Carlo et al. (2024), Robinson et al. (2005), and Singh and Tripura (2023). Certain studies also reported application-specific limitations due to shallow penetration and anthropogenic influence (Thapa et al., 2019; Zarroca et al., 2011) and limited clarity in conductive

TABLE 4 Factors influencing groundwater recharge estimation through geophysical survey methods.

Factors	Characteristics	Geophysical survey methods		
		Electrical resistivity tomography (ERT)	Electromagnetic (EM) survey	Ground penetration radar (GPR)
Subsurface heterogeneity	Lithology variation (clay, sand or gravel layers)	Reduce resolution and distort signals resistivity (Gottschalk et al., 2017)	Distort signals and affect the conductivity data (Binley et al., 2015)	Attenuate signals (Kumar et al., 2025)
Conductivity of soil and rocks	Subsurface materials influence signals penetration, affects penetration depth	Conductivity dynamics mispresent resistivity data (Yassin et al., 2014)	Limits penetration depth in high conductive soils (Leucci, 2008)	Limits resolution and depth of penetration (Leucci, 2008)
Electrode and ground contact	Good contact leads to accurate measurements	Poor contact leads to inaccurate readings, affected by soil moisture conditions (Rücker and Günther, 2011)	–	–
Surface conditions (topography)	Electrodes placement is difficult in rough and uneven surface	Placement significantly affects the accuracy and data quality (Lu et al., 2015)	–	Results in scattering and affects data quality (Cassidy and Jol, 2009)
Seasonal and temporal variability/ weather conditions	Groundwater level and soil moisture dynamics, EM signals quality is affected by soil conductivity due to rain and soil moisture variations	Resistivity is influenced by temporal changes and time-lapse survey is needed (Boddice et al., 2017)	Affects readings, survey repeatability and consistency (Boddice et al., 2017)	–
Cultural and environmental noise	Metal objects, power lines and infrastructure interference	–	Data skewness, requires mitigation strategies (Reynolds, 2011)	
Depth and frequency	Depth and resolution of survey depends on frequency	–	The higher the frequency shallow and detailed will be the resolution and vice versa (Arato, 2013)	–
Signal attenuation	Signal strength lost in wet clay (conductive environment)	–	–	Reduce survey depth and data effectiveness (Annan, 2005)
Water table depth	Affects performance	–	–	More powerful GPR system is needed for deep water tables (Bentley and Trenholm, 2002)
Soil properties	Type, texture, and composition	Affects the signals propagation (Vanderborght et al., 2013)		
Depth of investigation	Sensors to target area distance	Increasing depth decreases accuracy with low resolution (Hasan et al., 2020)		

layers need for improved petrophysical models (Gómez et al., 2019). ERT faces certain challenges regarding data reliability due to electrodes mislocution distorting tomographic images, noise sensitivity, and environmental factors interfering in data interpretation. Some spatial constraints for electrode array like vegetation, compaction, pipes, fences and time consumed during large survey due to resolution issue in detecting shallow water without small electrode spacing (Oldenborger et al., 2005). GPR contains some limitations related to conductive soils compared to ERT and depth of penetration in saturated soils due to high attenuation of radar signals (Toushmalani et al., 2010). The TEM resolution decreases in depth, inefficient resistive materials and challenges in laterally or near-vertically confined structures (Binley et al., 2015).

4 Conclusion and way forward

Groundwater research via geophysical methods is a valuable tool for monitoring the world's underground freshwater supplies. Climate change has had and will continue to have an impact on the groundwater recharge rates and withdrawals for human usage. The effects of the changing climate will undoubtedly have lasting implications on the groundwater resources of all biomes and affect all strata of life on planet earth. Groundwater exploration, monitoring, and mapping are essential areas of research that can help better understand the resources underneath our feet. It is for this reason that a scoping review of three prominent geophysical methods for imaging subsurface structure and water saturation was needed. This paper lays the foundation for those within the geophysical community to see the work that has been done, as well as trends that are emerging. A cursory discussion of the three prominent methods (ERT, EM, and GPR) was detailed in the paper for audiences unfamiliar with geophysical tools. The study ties into a broader concept of a scoping review with a PRISMA diagram showing the methodology and selection criterion for examining current research publications available. The results of the study yielded graphical data that was analyzed for trends. These trends reveal an increase in groundwater geophysical surveying worldwide indiscriminate of climate or geography. The study points to the idea that climate change is altering where these surveys are being conducted and pointing to larger climatic issues of the changing landscape around us. For example, the expanding of arid environments into areas that were once subtropical or the peril the Mediterranean climate is in as it slowly converts to a more arid climate are just two examples of the scientific community surveying sites changing with the climate. These are all factors that drive research and publications in groundwater geophysical surveying. The discussion section of the paper delves into nuances of socioeconomics that show disparity in what countries are publishing surveys.

The geological setting affects the performance of geophysical methods and choice of methods. Most studies used ERT followed by EM and GPR. Investigation depth was greatest for EM followed by ERT and GPR. The 2D ERT configuration was found to be the maximum followed by pole-dipole and dipole–dipole, VES, TDEM and Wenner array. Various influencing factors including subsurface heterogeneity and high material conductivity often reduce resolution and distort signals. Resistivity and EM measurements are affected by salinity and saturation while GPR signals are attenuated in saturated and saline conditions. ERT data quality is affected by poor electrode-ground contact topography and cultural noise. Seasonal variability and frequency-depth trade-offs affect resolution and accuracy of surveying methods. Effectiveness and repeatability of the geophysical surveys methods are influenced by weather conditions and water table depth. Considering these factors, an adaptable and well-planned geophysical survey method selection in diverse geological setting can enhance the precision of groundwater recharge estimation.

These geophysical methods are crucial for subsurface investigation and valuable insight into groundwater resources contamination, transport, and lithological variations. Each geophysical method offers unique strengths. ERT covers subsurface profiling but is sensitive to electrode contact and heterogeneity. For conductive zones EM surveys are very effective in conductive zones through the penetration depth in resistive materials is limited. GPR offers valuable investigations in mapping shallow groundwater. Despite the limitations including resolution issues, environmental interference and the potential gap for extensive validation, sensors technology advancement, data and models' integration and machine learning are the avenues to overcome these challenges. Multimethod approach, calibration accuracy, interdisciplinary collaborations can optimize more accurate and reliable estimation of subsurface rechange and processes. Understanding the factors and limitations of the geophysical survey methods for groundwater recharge estimation is important for selecting the more suitable method and/or integration of methods for improving recharge estimation accuracy.

Based on current synthesis of geophysical methods applications, future research could explore machine learning and artificial intelligence models' integration to process large geophysical and hydro-environmental datasets thereby improving the interpretation and spatial resolution of recharge zones mapping. Quantum sensor technologies development can increase precision and accuracy measurement. Unmanned aerial vehicles (UAVs) or drones' integration into geophysical technologies can improve accessibility. Another possible solution is to combine all the geophysical methods to mitigate the individual limitations. Integration of models and AI-driven analytics with geophysical techniques can facilitate real-time monitoring with accuracy and efficiency of the assessment. The trend line slope of groundwater geophysical surveys shows no sign of slowing down in the coming years. Future work in this area will likely include maintaining updated reviews of the new technology that emerges from all corners of the globe. Geophysical tools adapt and change with time, and with the advent of additional global climate issues, this technology will be dependent on groundwater analysis more than ever. The historical climate areas are changing, and therefore, water stress/demand will change accordingly. This will provide a space for future work to observe trends in publications and, perhaps more importantly, what drives the trends seen in the future.

Author contributions

NA: Methodology, Conceptualization, Investigation, Writing – review & editing, Data curation, Writing – original draft, Formal analysis, Visualization. JC: Writing – original draft, Data curation, Writing – review & editing, Formal analysis, Visualization, Investigation, Methodology, Resources. GS: Writing – review & editing, Investigation, Writing – original draft, Data curation, Formal analysis, Visualization, Methodology. GR: Investigation, Formal analysis, Methodology, Writing – review & editing, Visualization, Data curation, Writing – original draft. AR: Writing – review & editing, Formal analysis, Writing – original draft, Investigation, Visualization, Data curation. YD: Conceptualization, Writing – review & editing, Funding acquisition, Supervision, Methodology, Project administration, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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