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Synergizing Geophysical Analysis and Geotechnical for Artificial Recharge Well and Aquifer Studies: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The harvesting of surface runoff stands as a pivotal process in artificially recharging groundwater, playing a crucial role in augmenting groundwater within aquifers. Groundwater recharge via recharge wells is one of the successful direct sub-surface methods. To pinpoint the most suitable locations for recharge wells, a combination of geophysical surveys, including Electrical Resistivity, Magnetic, and Electrologging surveys, was used. These geophysical surveys serve as essential tools for comprehending the sub-surface lithology and played a pivotal role in identifying distinct aquifers and determining their respective dimensions, thereby aiding in the precision of recharge well placement. Our objective is to review the various methods to assess the underground water storage capacity of the aquifer based on tests viz. Sieve Analysis, Soil Water Retention Capacity, and Lateral Permeability tests. These combination of theoretical and practical evaluations aim to determine the aquifer's potential for storing groundwater. Geophysical surveys are invaluable for deriving various relationships through diverse analyses. Moreover, exploring the correlation between geophysical methods, such as electrical resistivity, and shear strength parameters is essential for comprehending the strength characteristics of subsurface layers.

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1. INTRODUCTION

Water scarcity is a global challenge, and sustainable water management practices have become imperative to meet the increasing demand for freshwater resources. The importance of groundwater as a vital resource has increased during the last half of the 20th century due to a variety of factors, including rotary drilling, submersible pumps, electricity distribution, population growth and concentration in urban areas, the need for increased food production, the pursuit of rural incomes and the avoidance of famine, and more. (OECD 2015). Managed Aquifer Recharge (MAR), aimed at improving both the quantity and quality of groundwater, was coined by British hydrogeologist Ian Gale. He served as the inaugural co-chair of the International Association of Hydrogeologists (IAH) Commission on Managing Aquifer Recharge from 2002 to 2011 (IAH-MAR 2018a).As many cities around the world face issues of water scarcity due to a fast and unsustainable urbanization, Groundwater recharge wells is an interesting relevant topic, especially in the arid and semi-arid area. In this context, rainwater harvesting has emerged as a crucial strategy to augment water supply and enhance groundwater recharge [1-4]. Geotechnical aspects play a pivotal role in the successful implementation of rainwater harvesting through artificial recharge wells and aquifer studies. Geotechnical engineering plays a crucial role in deciphering the geological nuances of a site, determining soil characteristics, and optimizing the well's structural integrity to ensure effective rainwater infiltration [5-10]. By looking at things like how easily water moves through the soil (permeability), the traits of the Underground water storage (aquifer), and the size of soil particles, we discover the important factors that make projects to refill groundwater successful [11-14]. These aspects help us understand what really matters in making artificial recharge wells work well and contribute to better and more sustainable ways of replenishing groundwater.

2. BACKGROUND AND CONTEXT

Rainwater harvesting is an ancient practice that has been employed by various civilizations throughout history. In Ancient Mesopotamia Civilization, built intricate systems to capture and store rainwater for agricultural purposes. The Romans were known for their advanced water management systems, including aqueducts and cisterns, to collect rainwater for domestic use. In regions like India and China, traditional rainwater harvesting techniquesincluded the construction of stepwells, tanks, and infiltration basins [15,16]. These structures facilitated the recharge of groundwater by allowing rainwater to percolate into the soil and replenish aquifers. In the 20th century, with advancements in engineering, there was a more systematic approach to groundwater recharge. Research studies began to focus on optimizing techniques for enhancing artificial recharge, including the use of recharge wells and basins.

3. RECHARGE WELL AND ITS IMPORTANT

Artificial recharge wells are structures designed to replenish groundwater aquifers by facilitating the intentional injection of water into the subsurface. This process is known as artificial groundwater recharge and is often employed in regions facing water scarcity or experiencing declining groundwater levels.The construction of recharge wells is essential for several reasons related to sustainable water resource management and addressing water scarcity.

I. **Ground water replenishment**: Recharge wells help replenish groundwater by allowing surface water to percolate into the underlying aquifer. This is particularly important in areas where groundwater extraction exceeds natural recharge rates.
II. **Mitigation of depletion**: Over-extraction of groundwater for various purposes, such as agriculture, industry, and domestic use, can lead to aquifer depletion. Recharge wells contribute to mitigating this depletion and maintaining sustainable groundwater levels.
III. **Enhancing aquifer storage capacity**: Constructing recharge wells increases the storage capacity of aquifers by allowing them to store surplus surface water during periods of abundance. This stored water can then be accessed during times of scarcity.
IV. **Improving ground water quality**: Recharge wells can help improve water quality by facilitating the natural filtration of surface water as it percolates through

the soil layers before reaching the aquifer. This process can remove impurities and contaminants.

V. **Aquifer:** An aquifer is a geological formation or underground layer of permeable rock, sediment, or soil that can store and transmit water. This subsurface reservoir allows water to move through it, and it can be a crucial source of groundwater. Aquifers are essential components of the Earth's hydrological cycle, as they store and release water in response to natural processes or human activities. Wells drilled into aquifers provide access to groundwater for various purposes, such as drinking water supply, irrigation, and industrial use. The properties of an aquifer, including its porosity and permeability, influence the movement and availability of water within it.

4. GEOPHYSICAL METHODS

Different researcher discusses the use of different geophysical methods to conduct geophysical investigations of lithology and groundwater potentials.Geophysical methods such as electromagnetism, ground-penetrating radar, and electrical resistivity have a minimal impact on soil structure. The measurements obtained introduce an initial layer of spatial variability, typically at a decametric or even hectometric scale. Electrical Resistivity Tomography (ERT) has found extensive application in hydrogeological investigations [17]. More recently, it has been employed to capture intricate images of water content and surface structure, providing a representation of hydrological processes [18] demonstrated the efficacy of Electrical Resistivity Tomography (ERT) in accurately delineating soil horizons and monitoring soil water movement during corn crop irrigation. Electrical resistivity is based on the measurement of the sub surface's resistance to the flow of electrical current. Different materials have varying resistivity values, allowing the method to detect contrasts in subsurface properties such as lithology, porosity, moisture content, and contaminant plumes. Electrical resistivity surveys typically employ arrays of electrodes to inject current into the ground and measure potential differences. Common instruments include resistivity meters, multi-electrode systems, and automated data loggers [19-23]. These instruments may vary in terms of electrode configurations, current injection methods, and data recording capabilities. Data acquisition involves deploying electrodes in the field according to a predefined survey design. This design may include different electrode configurations (e.g., Wenner, Schlumberger, dipole-dipole) optimized for specific objectives such as depth of investigation or lateral resolution. During data acquisition, electrical current is injected through one set of electrodes, and potential differences are measured using another set. Electrical resistivity surveys have a wide range of applications in geology, hydrogeology, environmental studies, engineering, and archaeology [24-26]. They are used for groundwater exploration and monitoring, delineation of contaminant plumes, mapping of geological structures, site characterization for construction projects, and locating buried archaeological features. There are other methods like Magnetic methods used in exploration for minerals, hydrocarbons, ground water, and geothermal resources. The method is also widely used in additional applications such as, regional and local geologic mapping (Finn, 2002), studies focused on water-resource assessment.

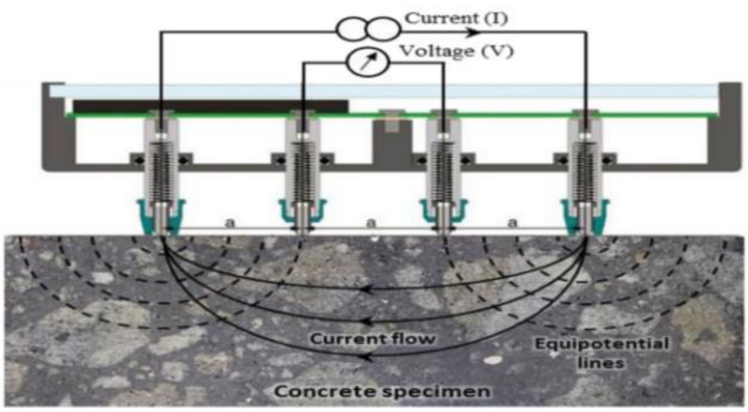

Fig. 1. Electrical resistivity configuration

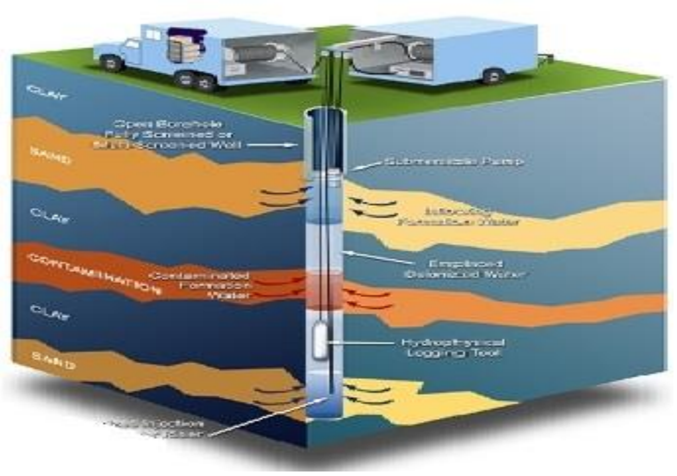

Fig. 2. Electrologging survey

Electrologging surveys also constitute a crucial method for comprehensive subsurface exploration, particularly when investigating various soil layers. This survey technique plays a vital role in providing detailed insights into the ground structure by employing electrical measurements, enabling a thorough understanding of diverse geological strata. Electrical logging tools can distinguish between different lithologies based on their electrical properties. For example, resistivity logs can differentiate between clay-rich formations (low resistivity) and sandstone or limestone formations (higher resistivity). This information is crucial for identifying potential aquifers and aquitards. The porosity of a formation, which represents the volume of pore space available for groundwater storage, can be estimated using electrical logging data. Formation porosity affects the electrical resistivity measured by logging tools, with more porous formations typically exhibiting higher resistivity values. Electrical logging surveys are widely used in the petroleum industry for reservoir evaluation, well logging, and formation evaluation. They are also employed in groundwater exploration and development, environmental site investigations, and geotechnical engineering studies.

5. LABORATORY TESTS

In the realm of aquifer and recharge well investigations, conducting essential laboratory geotechnical tests is imperative to comprehend soil properties and subsurface structure. These tests, including but not limited to grain size distribution, soil permeability, and water retention capacity, play a crucial role in enhancing the efficacy of water recharge and storage potential. Such thorough assessments are vital for optimizing the construction of recharge wells.

5.1 Grain size Distribution (IS 2720-4 (1985)

Critically examines the significance of grain size distribution in soils within aquifer systems, focusing on its pivotal role in the planning and execution of artificial recharge wells. As an essential factor influencing the success and efficiency of groundwater replenishment projects, a detailed analysis of soil grain sizes contributes to optimal well design. Coarse-grained soils such as sand and gravel typically have high permeability and porosity. They allow water to flow more easily and are well-suited for storing and transmitting groundwater. Primarily the composition of coarse and medium sand plays a pivotal role in facilitating groundwater flow and storage within the aquifer.

5.2 Water Retention Capacity (IS 14765-2000)

The water retention capacity of soil in an aquifer refers to the ability of the soil to retain water. It is a crucial property that influences the storage and availability of groundwater in the subsurface. The texture of the soil, whether it is coarse-grained (e.g., sand) or fine-grained (e.g., clay), significantly influences water retention. Understanding the water retention capacity of soil in an aquifer is crucial for managing groundwater resources, designing artificial recharge systems, and assessing the overall effectiveness of groundwater storage. Site-specific characteristics, geological conditions, and soil properties must be considered for accurate evaluations and sustainable groundwater management practices.

5.3 Permeability (IS 2720-17)

The permeability of soil in an aquifer plays a crucial role in determining the aquifer's potential for storing and transmitting groundwater. Permeability is a measure of how easily water can move through the soil or rock formation, and it directly influences several aspects of aquifer behavior. Soil with high permeability allows for faster groundwater flow. This is critical for aquifers as it influences how quickly water can recharge the aquifer or be extracted from it. Permeable soils facilitate efficient infiltration of precipitation and surface water into the aquifer. This is essential for recharging groundwater levels, maintaining aquifer storage, and sustaining water availability. The coefficient of permeability exhibits a wide range of values up to 10 orders of magnitude from coarse to very fine grained soils [27]. Moreover, past investigations on the coefficient of permeability indicate significant variability within the same deposit, with a coefficient of variation reaching as high as 240%.The coefficient of permeability was also computed using the grain size distribution, void ratios, and particle shape by means of the correlations proposed by (Carrier et al) [28]. (Onur et al) [29] found that uniformly graded sands have higher permeabilities compared to well graded sands as the smaller soil particles fill the voids between the larger ones. The coefficients of curvature and uniformity serve as indicators for characterizing the uniformity level of coarse-grained soils. In this paper, the coefficient of permeability evaluated using the (Hazen et al) [30] and (Carrier et al) [28] formulae yielded relatively good results in the uncemented sand layer.

Shishaye & Abdi et al [31]. The paper discuss about use of ground investigation using geophysical methods. Groundwater exploration is the investigation of underground formations to understand the hydrologic cycle, know the groundwater quality, and identify the nature, number and type of aquifers. There are different groundwater exploration methods. Surface geophysical methods constitute a groundwater investigation approach. Electrical resistivity method is one of the surface geophysical survey methods. This paper explores the application of geophysical surveys for delineating optimal locations for water well placement. The focus is on employing geophysical techniques to assess subsurface characteristics, aiding in the identification of areas with high groundwater potential. The study delves into the diverse array of geophysical methods utilized to map subsurface features, providing valuable insights for effective water well sitting and resource management.

Fig. 3. Water retention capacity as per IS 14765

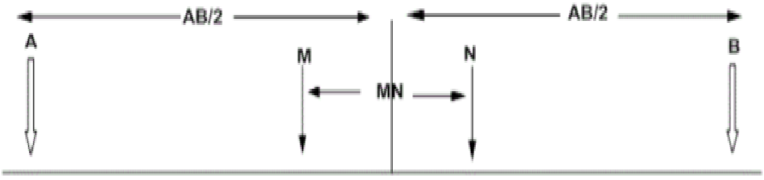

Fig. 4. Schlumberger array configuration

In this paper the survey employs the Schlumberger array configuration, utilizing the SARIS 1000 apparatus for data collection. This method harnesses the Schlumberger array's specific electrode arrangement to gather geophysical data effectively, enhancing the precision and reliability of the survey's results. In this study a total 7 VEStest are performed to find a suitable site location of wells. The Schlumberger electrode configuration with maximum half current electrode separation (AB/2) of 100 to 150 m was used for the survey.

From the result obtained the aquifer exhibits varying thickness, with a minimum depth of 28-38 meters registering a thickness of 13.7 meters, while its maximum thickness of 52.3 meters is observed at a depth range of 54-64 meters.

Musa et al [32], In this paper Vertical Electrical Sounding (VES) with Schlumberger configuration were conducted in North-western Nigeria. The Area is overlain Formation which consists of massive clays, clay grits, sandstones, mudstones and siltstones. A total of forty (40) VES was carried out in the study area with maximum electrode spacing of 200m. Using (Winrest) software in the sedimentary formation of the study area to demarcate ground water potential recharge zones. Maximum of five geoelectrical layers (clay latoritic top soil, sand, clay, weathered granite, fresh granite) of different lithology were delineated from the VES data. The groundwater potential zones were categorized based on the likelihood of discovering groundwater in the study area, ranging from poor to moderate and good zones. The middle section of the area exhibits low resistivity and substantial aquifer thickness, characterizing it as a productive water-bearing zone referred to as a good groundwater potential recharge aquifer. The result shows that an Aquifer lies within the weathered granite with thickness of 34-44m and depth 30-46m. Aquifer in the area mostly located within sandy clay, shale & weathered granite. The alluvial deposit of sand, sandy clay, sand stone & mud stone are best prospect for ground water potential.

Patel et al [33] & Desai et al [34]. This paper includes an Analytical solution, Numerical Empirical approaches, In-situ test results to predict recharge (rate) of the ground-water and capacity of recharge well which is essential for the proper management of suitable artificial ground-water recharge systems to maintain water balance and stop salt water intrusion. The authors have developed analytical equations to predict the expansion and recession of the groundwater mound. These predictions depend on the recharge rate intensity (Q_r) across various values of permeability (k), depth of pervious strata (H), and well diameter (d). Furthermore, the study investigates the impact of fluctuations in geotechnical parameters on water-tablevariations.Analytical approach

$$Q_r = 55 \times d \times k$$

Where Q_r is recharging flow

Recharge rate can be estimated from empirical formula as:

$$Q_r = (h_0^2 - h_n^2) \times k/2L$$

Where, h_0 = Height of phreatic water table above aquifer base in well (m); k = Co-efficient of permeability (m/sec); L= Influence zone or Radius of spread (m).

M.S. Pendke et al &Baviskar et al [35]. In this paper an artificial well recharge system model was designed and constructed near open well for groundwater enhancement. The filter unit was designed and constructed near the open well at demonstration field. The filter unit consists of three blocks, one is called primary filter (0.6mx 0.6m) which is combined with layers of stones, sand and gravels. The filter collects major sediments from runoff water. Primary filter is joined by 4” diameter pipe to silt trapping unit / energy dissipation unit (1.1m x 1m x 1.5 m) having a rectangular notch opening in main filter unit. The third block serves as the primary filtration tank, measuring 2m x 2m x 2m. It comprises three layers of distinct filter materials:

Table 1. Relationship between permeability, well diameter and discharge

k m/hr	5	4	3.86	3.6	2.7	1.8	0.36
d(m)				Q_rm^3/hr			
0.15	41.25	32.67	31.84	29.7	22.28	14.85	2.97
0.2	55	44	42.46	39.6	29.7	19.8	3.96
0.25	68.7	54.45	53.08	49.5	37.13	24.75	4.95
0.3	82.5	65.34	63.69	59.4	44.55	29.7	5.94

a 30 cm layer of sand, followed by 30 cm of gravel, and finally, 30 cm of stones.The main filter unit is joined to open well by the 4" diameter PVC pipe. The filter unit is constructed with brick walls and cement concrete (2m x 2m x 2 m). The results of present study with respect to specific gravity, filtration efficiency and its effect on groundwater potential are as follows.

The specific gravity was determined and found to be 2.51 for collected soil samples. Specific gravity data are useful to calculate the velocity of runoff water flowing through the filtration unit. The minimum and maximum values of velocity were determined as 8.228 x 10^{-3} m/s and 8.228 x 10^{-5}m/s with an average velocity value 411.40 x 10^{-5} m/s. The depth of 90 cm of the filtration unit was considered as three layers of sand, gravel and stones arranged one above another with constant thickness of 30 cm each. At the bottom stones were arranged and above gravel and sand was arranged. The filtration efficiency of primary filter was determined and found to be in tune of 64 to 70% and for main filter 90 to 94%. The availability of 25 to 35% surface runoff for well recharging was found to be useful to build up groundwater table from 0.3 to 3.4 m.

Geophysical methods are valuable for establishing correlations between electrical resistivity and geotechnical parameters, offering an indirect yet insightful means of understanding soil properties. Siddiqui et al [36]. This paper discuss about Precise determination of engineering properties of soil is essential for proper design and successful construction of any structure (Cosenza et al. 2006 Traditional methods for assessing engineering properties are invasive, expensive, and time-intensive. Electrical resistivity surveys offer an appealing non-intrusive approach to delineating subsurface properties without disrupting the soil. Establishing reliable correlations between electrical resistivity and other soil properties allows for effective subsurface soil characterization without the need for borehole sampling. This paper outlines correlations between electrical resistivity and various soil properties. In this paper a total of 79 soil samples were obtained from ten (10) boreholes (BH-01 to BH-10) and brought to geotechnical laboratory for various soil tests (e.g. moisture content, unit weight, direct shear, sieve analysis, laboratory resistivity test).

The findings from both field and laboratory electrical resistivity tests, along with traditional laboratory tests, were collectively analyzed to comprehend the interconnections between electrical resistivity and diverse soil properties. The evaluation of test results was conducted using both simple and multiple regression analyses. Direct shear test, cohesion for silty sand ranges from 3.63 to 68.23 kPa, friction angle 5.36 and 42.51 degree, cohesion for sandy soil is 0.00 and 17.41 kPa and average cohesion is 5.25 kPa, friction angle value is 26.10 to 42.50 degree.

Relation between laboratory and field resistivity vale is

$$P_L = 0.710P_f + 313.2.$$

Relation between cohesion and resistivity is

$$C = 18.986 - 0.005P + 14.625W.$$

Relation between friction angle and resistivity is

$$\Phi = 39.187 + 0.001P - 61.336W.$$

Where P is resistivity of soil, and W is water content of soil sample in %.

From the data analysis, significant quantitative and qualitative correlations have been obtained between resistivity and moisture content, friction angle and. weaker correlations have been observed for cohesion, unit weight of soil.

6. RESULTS AND DISCUSSION

In this study, the focus lies on recharge well and aquifer investigations, utilizing a range of geophysical and geotechnical tests. Geophysical surveys pinpoint optimal aquifer locations with high water storage potential by analyzing resistivity values across various subsurface layers. By adhering to standards like IS and ASTM, distinct resistivity readings reveal different material compositions. Geophysical methods also aid in identifying freshwater sources underground.

Geotechnical tests complement these findings by assessing soil and subsurface properties. Grain size distribution tests determine soil composition percentages (coarse, medium, and fine sand) against permissible limits. Water retention capacity tests gauge a soil's ability to retain water, crucial for understanding pore structure and suction. Permeability tests, crucial in recharge well studies, assess water flow through different soil layers, shedding light on water distribution capabilities.

This comprehensive approach enhances understanding of aquifer properties and aids in strategic decision-making for recharge well implementation.

7. CONCLUSION

The synergy of geophysical and geotechnical methods is crucial for optimizing the performance of recharge wells and ensuring their effectiveness in augmenting groundwater resources. To discern the material properties of the aquifer and evaluate the soil's water storage capacity, essential geotechnical tests such as grain size distribution and water retention capacity assessments are imperative. These tests play a pivotal role in unveiling the inherent characteristics of the aquifer material and determining the soil's capacity to effectively retain and store water. Conducting a permeability test is crucial to understanding the fluid flow dynamics within aquifer layers. This test is instrumental in revealing how water moves through different materials, with higher permeability indicating a greater potential for efficient water flow. In essence, the permeability test serves as a key determinant of the aquifer's hydrogeological behavior. Ultimately, geotechnical testing serves to reinforce the reliability of geophysical surveys and bolster our research endeavors.

In conclusion, the synergistic application of diverse geophysical surveys and comprehensive geotechnical tests is essential for optimizing the construction of recharge wells. This integrated approach ensures a thorough understanding of subsurface conditions, enhancing the overall effectiveness and success of recharge well implementation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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