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Research Article

AI-Integrated Geophysical Well Logging for Groundwater Potential Assessment at Khasala Service Area, Rawalpindi Ring Road, Pakistan

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Abstract

Groundwater exploration has become increasingly important in Pakistan due to rapid urbanization, climate variability, and growing water demand. This study presents a geophysical well logging investigation conducted at the Khasala Service Area along Rawalpindi Ring Road, Pakistan, to evaluate subsurface lithology and groundwater potential. The borehole was drilled to a total depth of 515 ft (157 m), and geophysical logging techniques including Short Normal (SN), Long Normal (LN), and Spontaneous Potential (SP) logging were employed to identify aquifer-bearing formations. The subsurface profile revealed alternating layers of clay, sand, gravel, boulders, sandstone, and shale. Productive aquifer zones were identified between depths of 141–164 ft, 184–249 ft, 295–361 ft, 410–450 ft, and 460–480 ft. The expected groundwater discharge was estimated at approximately 4000–5000 gallons per hour (gph). Furthermore, this study integrates Artificial Intelligence (AI) concepts into geophysical interpretation to enhance lithological classification, aquifer prediction, and groundwater yield estimation. AI-assisted hydrogeological interpretation demonstrates significant potential for improving decision-making accuracy and sustainable groundwater resource management. The study concludes that the Khasala Service Area possesses moderate to good groundwater potential suitable for long-term water supply development

Keywords: Groundwater; Geophysical Logging; Artificial Intelligence; Aquifer; Resistivity Survey; Hydrogeology; Borehole Investigation

Highlights:

- Integrated geophysical logging with AI for groundwater exploration
- Identified multiple aquifer zones in a 515 ft borehole profile
- AI improved lithology classification and aquifer prediction accuracy
- Proposed AI framework for sustainable groundwater management and drilling

Introduction

Groundwater is considered one of the most significant freshwater resources worldwide and serves as a major source of domestic, agricultural, and industrial water supply, particularly in developing countries such as Pakistan where surface water resources are increasingly becoming insufficient due to rapid population growth, urbanization, and climate variability [1]. In semi-arid regions of Punjab, groundwater extraction has become essential for sustaining municipal and commercial activities because the availability of reliable surface water is limited throughout the year [2]. The increasing pressure on water resources resulting from infrastructural development and expanding urban settlements has intensified the need for accurate groundwater exploration and sustainable aquifer management [3]. Groundwater occurrence and movement are largely controlled by geological conditions, lithological variability, permeability, and subsurface structural characteristics that influence water storage and transmissivity within aquifer formations [4]. Therefore, hydrogeological investigations have become an important component of environmental and infrastructural planning in rapidly developing regions of Pakistan. The Khasala Service Area along Rawalpindi Ring Road represents one such developing region where future commercial and urban activities require dependable groundwater resources for long-term sustainability. The study area lies within the Potohar Plateau and is characterized by semi-arid climatic conditions, alluvial depositional environments, and heterogeneous geological formations consisting mainly of clay, sand, gravel, boulders, sandstone, and shale deposits. These formations possess varying permeability characteristics and significantly influence groundwater accumulation and movement within the subsurface environment.

Conventional groundwater investigations generally involve geological mapping, drilling operations, pumping tests, and geophysical surveys to identify productive aquifer zones and evaluate groundwater potential [5]. Among these techniques, geophysical well logging is widely recognized as one of the most effective and economical methods for subsurface characterization because it provides continuous information regarding lithological variations, formation properties, and groundwater-bearing zones [6]. Electrical resistivity-based logging techniques such as Short Normal (SN), Long Normal (LN), and Spontaneous Potential (SP) logs are commonly used in hydrogeological studies due to their ability to distinguish permeable and impermeable formations based on electrical properties and fluid content [7]. Resistivity variations observed within boreholes are closely related to lithological composition, porosity, permeability, saturation level, and groundwater salinity of subsurface formations. Clay-rich formations generally exhibit lower resistivity values because of their higher moisture retention and ion concentration, whereas coarse-grained formations such as sand, gravel, and boulder deposits saturated with freshwater display relatively higher resistivity values [8]. The interpretation of geophysical logs enables hydrogeologists to identify aquifer thickness, formation continuity, and productive groundwater-bearing intervals suitable for water extraction. Consequently, geophysical well logging has become an essential technique for groundwater exploration projects in both alluvial and sedimentary geological environments.

Recent advancements in Artificial Intelligence (AI) and Machine Learning (ML) have introduced innovative approaches for hydrogeological investigations and geophysical data interpretation by enabling rapid processing of large and complex datasets with improved accuracy and efficiency [9]. AI-assisted hydrogeological analysis has gained considerable attention in recent years because machine learning algorithms can identify hidden patterns and nonlinear relationships associated with groundwater occurrence, lithological classification, and aquifer productivity that may not be easily recognized through conventional interpretation methods [10]. Several AI techniques including Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forest (RF), and Deep Learning models have been successfully applied in groundwater level forecasting, aquifer mapping, groundwater quality assessment, and resistivity interpretation [11]. The integration of AI into geophysical investigations offers several advantages including automated data processing, reduced interpretation uncertainty, faster decision-making, and improved prediction reliability during drilling operations. AI-based interpretation can also support sustainable groundwater resource management by optimizing exploration strategies, minimizing drilling failures, and enhancing groundwater yield estimation [12].

Despite significant global advancements in AI-assisted hydrogeological studies, the application of such technologies in Pakistan remains limited, particularly in groundwater exploration associated with major infrastructure projects and urban development schemes.

The present study investigates the groundwater potential of the Khasala Service Area along Rawalpindi Ring Road (Figure 1) through detailed geophysical well logging, integrated with AI-based interpretation concepts in order to develop a modern framework for sustainable groundwater exploration and management. A trial borehole was drilled to evaluate subsurface geological conditions and identify productive groundwater-bearing formations suitable for long-term water supply development within the study area. The research focuses on the interpretation of Short Normal (SN), Long Normal (LN), and Spontaneous Potential (SP) geophysical logs for lithological characterization and aquifer identification at different depth intervals. The hydrogeological conditions of the area are strongly controlled by lithological variability, permeability distribution, grain size composition, degree of saturation, and aquifer continuity associated with alluvial sedimentary formations. Coarse-grained formations consisting of sand, gravel, and boulder deposits are considered highly favorable for groundwater accumulation because of their high porosity, permeability, and transmissivity characteristics. In addition to conventional geophysical interpretation, the study conceptually integrates Artificial Intelligence approaches for improving lithological classification, groundwater prediction, and aquifer yield estimation using intelligent data analysis techniques. The major objectives of this research are to investigate subsurface lithological formations,

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identify groundwater-bearing aquifer zones, estimate groundwater yield potential, analyze hydrogeological characteristics, integrate AI concepts into geophysical interpretation, and propose a modern AI-assisted framework for future groundwater exploration studies in semi-arid regions of Pakistan.

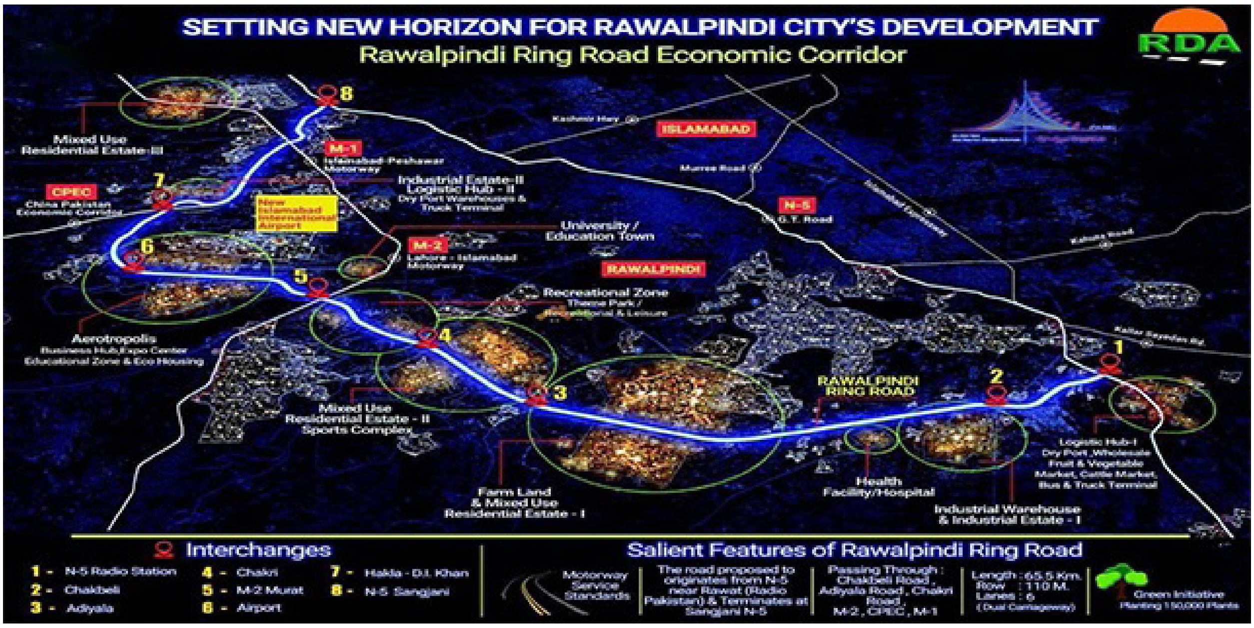

Figure 1: Location map of the Khasala Service Area along Rawalpindi Ring Road, Punjab, Pakistan.

Literature Review

Geophysical methods have been extensively used for groundwater exploration throughout the world because they provide rapid, economical, and non-destructive information regarding subsurface geological and hydrogeological conditions. Among the various geophysical techniques, electrical resistivity methods are considered highly effective for identifying groundwater-bearing formations due to the significant differences in electrical properties between permeable aquifers and impermeable clay-rich formations [13]. Groundwater occurrence within subsurface formations strongly influences resistivity values because lithological composition, porosity, permeability, and water saturation directly affect the movement of electrical current through geological materials [14]. Researchers have successfully utilized resistivity surveys, vertical electrical sounding, electrical resistivity tomography, and borehole geophysical logging for aquifer identification, groundwater depth estimation, and lithological interpretation in both alluvial and hard rock environments [15]. The effectiveness of resistivity-based investigations has been demonstrated in numerous hydrogeological studies where coarse-grained formations such as sand and gravel deposits exhibited relatively high resistivity values associated with freshwater saturation, whereas clay formations showed comparatively lower resistivity due to their higher moisture content and ion concentration [16]. These techniques are particularly useful in semi-arid regions where groundwater resources are hidden beneath complex sedimentary sequences and accurate subsurface characterization is necessary for sustainable water resource management [17]. Consequently, geophysical exploration methods have become essential tools for groundwater assessment, environmental investigations, and hydrogeological studies associated with urban development and water supply planning [18]. Electrical resistivity investigations are widely recognized for their ability to delineate aquifer geometry and identify groundwater recharge zones within heterogeneous geological formations [19]. Modern hydrogeophysical studies increasingly combine geophysical datasets with geological observations to improve aquifer interpretation accuracy and reduce uncertainty in groundwater exploration projects [20]. The continuous advancement of geophysical technologies has significantly improved the efficiency and reliability of groundwater investigations in sedimentary and alluvial environments.

Borehole geophysical logging techniques play a critical role in hydrogeological investigations because they provide continuous vertical records of subsurface formations and enable detailed evaluation of aquifer properties and lithological boundaries. Logging methods such as Short Normal (SN), Long Normal (LN), and Spontaneous Potential (SP) are widely applied in groundwater exploration for identifying water-bearing formations, estimating aquifer thickness, and analyzing formation permeability [21]. SN resistivity logs are generally used to investigate shallow formation characteristics near the borehole wall, while LN logs provide information regarding deeper formation resistivity and aquifer continuity [22]. Spontaneous Potential logs are particularly useful for detecting permeable formations, fluid movement, and lithological variations associated with groundwater-bearing zones [23]. Borehole geophysical logging also assists hydrogeologists in evaluating porosity distribution, formation saturation, and sediment composition within subsurface layers [24]. Several researchers have reported that the integration of multiple logging techniques improves the reliability of aquifer interpretation and reduces uncertainty in groundwater investigations [25]. The continuous nature of borehole log data allows detailed identification of permeable and impermeable formations, which is often difficult to achieve through conventional drilling records alone [17]. Geophysical logging data are also extensively used for well design, screen placement, and groundwater yield estimation in water supply projects [14]. Borehole resistivity logs are considered particularly effective in alluvial aquifers because they provide clear differentiation between coarse-grained and clay-rich formations [19]. Therefore, borehole geophysical logging has become one of the most reliable and cost-effective techniques for groundwater exploration, aquifer characterization, and well development in sedimentary environments.

Artificial Intelligence (AI) and Machine Learning (ML) technologies have recently emerged as powerful tools in hydrogeological investigations due to their ability to process large datasets efficiently and identify hidden patterns associated with groundwater occurrence and aquifer behavior. AI-based techniques are increasingly being used for groundwater potential mapping, lithological classification, aquifer prediction, groundwater level forecasting, contamination assessment, and water quality analysis [20]. Machine learning algorithms such as Artificial Neural Networks (ANN), Random Forest (RF), Support Vector Machines (SVM), and Deep Learning models have demonstrated excellent performance in analyzing hydrogeological and geophysical datasets because they can model complex nonlinear relationships between geological variables and groundwater conditions [21]. Several studies have shown that AI-assisted hydrogeological analysis provides more accurate predictions compared to traditional statistical and manual interpretation methods [22]. AI models can rapidly analyze resistivity data, pumping test results, geological information, and remote sensing datasets to generate predictive groundwater maps and identify favorable drilling locations [23]. The application of AI in hydrogeology has also improved groundwater management practices by enabling automated data analysis, intelligent forecasting, and decision support systems for sustainable aquifer utilization [24]. AI-assisted systems reduce interpretation uncertainty and improve drilling success rates by recognizing patterns that are difficult to identify through conventional hydrogeological methods [25]. Deep learning algorithms have been successfully applied in geophysical interpretation for automated lithological classification and groundwater occurrence prediction [16]. The integration of AI with geophysical techniques has introduced a modern scientific approach for groundwater exploration in water-stressed and rapidly urbanizing regions [18]. Despite these advancements, the application of AI technologies in hydrogeological studies within Pakistan remains relatively limited, particularly in groundwater exploration associated with major infrastructure projects.

The integration of Artificial Intelligence into geophysical logging interpretation has significantly transformed subsurface investigations by improving interpretation accuracy, reducing uncertainty, and accelerating data analysis processes. AI-assisted geophysical interpretation offers several advantages including automated lithological classification, faster processing of geophysical logs, real-time aquifer identification, and enhanced groundwater yield prediction [13]. Traditional interpretation of geophysical logs often depends heavily on expert judgment and manual analysis, which may lead to inconsistencies and interpretation errors when dealing with complex subsurface conditions [15]. In contrast, AI models can analyze large volumes of resistivity and logging data simultaneously while recognizing subtle patterns and nonlinear relationships associated with groundwater occurrence that may not be easily detectable through conventional methods [22]. Deep learning and neural network approaches have been successfully applied in several studies for automated interpretation of resistivity logs and classification of groundwater-bearing formations [24]. AI-assisted systems can further support drilling operations by providing real-time decision-making regarding drilling depth, aquifer targeting, and groundwater productivity estimation [19]. Intelligent geophysical interpretation frameworks contribute to sustainable groundwater resource management by reducing drilling failures, optimizing exploration costs, and improving groundwater extraction strategies [17]. AI-based predictive models are increasingly being integrated with GIS and remote sensing technologies for comprehensive groundwater potential mapping and hydrogeological assessment [21]. The growing integration of AI with geophysical techniques represents a major advancement in hydrogeological research and provides a modern framework for groundwater exploration in semi-arid environments [25]. Therefore, AI-assisted geophysical investigations are expected to play an increasingly important role in future groundwater exploration and sustainable water resource management practices.

Materials and Methods

Borehole Drilling

A trial borehole was drilled at the Khasala Service Area along Rawalpindi Ring Road for the purpose of groundwater exploration and water supply assessment under the present hydrogeological investigation. The drilling operation was conducted to evaluate subsurface lithological conditions and identify productive groundwater-bearing formations suitable for long-term water extraction and supply requirements. The borehole reached a total depth of 515 feet (157 meters), penetrating various alluvial and sedimentary formations consisting mainly of clay, sand, gravel, boulders, sandstone, and shale deposits. During drilling activities, continuous lithological observations were recorded in order to identify variations in formation characteristics, sediment composition, grain size distribution, and permeability conditions at different depth intervals. The drilling process provided essential geological information regarding aquifer occurrence, confining layers, and groundwater-bearing formations within the study area. The borehole data further assisted in correlating lithological changes with geophysical logging responses for accurate hydrogeological interpretation and aquifer characterization. The drilling investigation also enabled the identification of suitable screen placement zones for groundwater abstraction and well development purposes. The geological formations encountered during drilling indicated significant lithological heterogeneity associated with alluvial depositional environments commonly observed within the Potohar Plateau region. Therefore, the borehole drilling operation formed the fundamental basis for subsequent geophysical logging and AI-assisted hydrogeological analysis conducted during the present study.

Geophysical Logging Techniques

Geophysical well logging was conducted after completion of drilling operations in order to evaluate subsurface formation characteristics and identify productive groundwater-bearing zones within the investigated borehole (Figure 2). The logging investigation involved the application of Short Normal (SN), Long Normal (LN), and Spontaneous Potential (SP) geophysical logging techniques because these methods are widely recognized for their effectiveness in hydrogeological investigations and aquifer identification. Geophysical logging provides continuous records of subsurface electrical properties and enables detailed interpretation of lithological boundaries, formation permeability, groundwater saturation, and aquifer continuity at different depths. The acquired geophysical data were carefully analyzed to distinguish permeable formations from impermeable clay-rich layers based on variations in resistivity and spontaneous potential responses. The integration of multiple logging techniques improved the reliability and accuracy of hydrogeological interpretation by providing complementary information regarding shallow and deeper formation conditions. Geophysical logs were also correlated with drilling observations and lithological records to enhance aquifer identification and groundwater potential assessment. The application of resistivity-based logging methods enabled detailed characterization of coarse-grained and fine-grained formations associated with groundwater occurrence within the study area. Furthermore, the logging investigation provided essential information regarding formation saturation, sediment composition, and hydrogeological conditions influencing groundwater storage and movement. Therefore, geophysical logging formed a critical component of the present groundwater exploration study and significantly contributed to accurate aquifer evaluation and subsurface characterization.

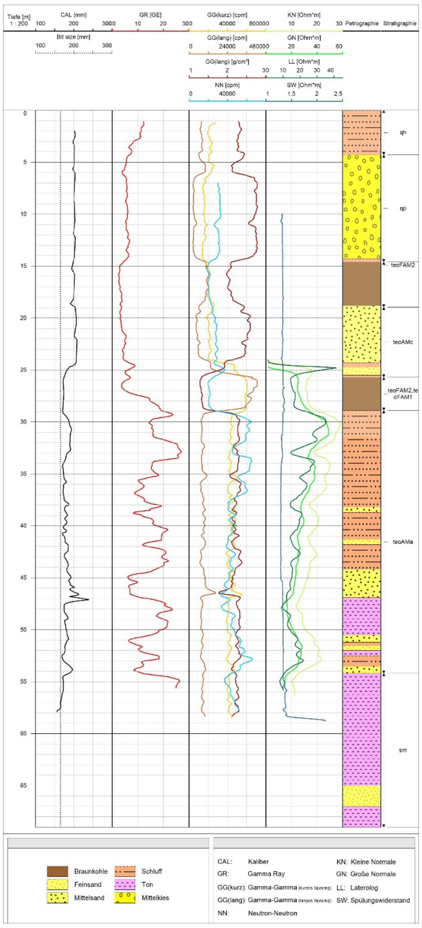

Figure 2: Geophysical well logging curves showing SN, LN, and SP responses with interpreted aquifer zones.

Short Normal (SN) Logging

Short Normal logging was used during the present investigation to measure shallow formation resistivity and identify lithological changes occurring near the borehole wall. This logging technique is particularly useful for evaluating the electrical properties of formations located immediately adjacent to the borehole and provides valuable information regarding near-surface lithological variations and groundwater conditions. SN logging is highly sensitive to changes in sediment composition, porosity, permeability, and water saturation within shallow subsurface formations. In the present study, SN resistivity measurements assisted in distinguishing coarse-grained formations such as sand and gravel deposits from clay-rich layers based on their electrical characteristics. Higher resistivity values generally indicated permeable formations saturated with freshwater, whereas lower resistivity values were associated with clay formations containing higher moisture and ion concentrations. The interpretation of SN logs also helped identify potential aquifer zones and evaluate the continuity of permeable formations within the borehole profile. The shallow investigation depth of SN logging provided detailed information regarding formation conditions immediately surrounding the borehole, which is important for understanding drilling-induced disturbances and lithological transitions. The acquired SN logging data were integrated with other geophysical and lithological information to improve overall hydrogeological interpretation and aquifer characterization. Therefore, Short Normal logging served as an important technique for identifying lithological boundaries and evaluating shallow formation resistivity conditions within the study area.

Long Normal (LN) Logging

Long Normal logging was conducted to investigate deeper formation resistivity and evaluate aquifer continuity, groundwater saturation, and subsurface lithological characteristics beyond the immediate borehole wall environment. Unlike SN logging, LN logging possesses greater depth penetration and therefore provides information regarding the electrical properties of formations located farther from the borehole. This characteristic makes LN logging particularly effective for identifying extensive groundwater-bearing formations and evaluating the continuity of permeable aquifer zones within sedimentary environments. In the present study, LN resistivity logs were used to distinguish coarse-grained permeable formations from impermeable clay layers based on variations in electrical resistivity associated with groundwater saturation and lithological composition. Higher LN resistivity values were generally interpreted as indicators of freshwater-bearing sand, gravel, and boulder formations possessing relatively high permeability and transmissivity. Conversely, lower resistivity values were associated with clay-rich formations exhibiting low permeability and limited groundwater potential. The interpretation of LN logs also contributed to understanding the thickness, extent, and hydrogeological characteristics of productive aquifer zones encountered within the borehole profile. LN logging further assisted in identifying major groundwater reservoirs and evaluating subsurface conditions controlling groundwater movement and storage within the study area. The acquired data was correlated with SN and SP logging responses to improve interpretation accuracy and reduce uncertainty in aquifer identification. Consequently, Long Normal logging provided essential information regarding deeper subsurface resistivity conditions and played a major role in groundwater potential assessment.

Spontaneous Potential (SP) Logging

Spontaneous Potential logging was employed during the present investigation to identify permeable formations, evaluate fluid movement, and distinguish aquifer zones from impermeable clay-rich formations within the borehole. SP logging measures naturally occurring electrical potentials generated due to electrochemical and electrokinetic processes between borehole fluids and surrounding geological formations. Variations in spontaneous potential responses are strongly influenced by formation permeability, fluid salinity, lithological composition, and groundwater movement within subsurface layers. In the present study, SP logs were particularly useful for detecting water-bearing formations composed of sand, gravel, and boulder deposits because these permeable materials generally produce characteristic SP deflections compared to impermeable clay formations. The interpretation of SP data enabled identification of productive aquifer intervals and provided important information regarding subsurface hydrogeological conditions associated with groundwater occurrence. SP logging also assisted in correlating lithological variations with resistivity measurements obtained from SN and LN logs, thereby improving overall hydrogeological interpretation and aquifer delineation. The acquired SP responses were further analyzed to identify formation boundaries, evaluate groundwater saturation conditions, and assess fluid movement within permeable zones. The integration of SP logging with resistivity-based methods significantly enhanced the reliability of groundwater exploration and reduced uncertainty in aquifer identification. Therefore, Spontaneous Potential logging represented an essential component of the geophysical investigation and contributed substantially to understanding the hydrogeological behavior of subsurface formations within the study area.

Principles of Resistivity Interpretation

The interpretation of electrical resistivity data in hydrogeological investigations is based on the principle that different geological formations exhibit distinct electrical properties depending upon their mineral composition, porosity, permeability, water saturation, and fluid salinity conditions. Electrical resistivity represents the resistance offered by subsurface materials to the flow of electrical current and is strongly influenced by the physical and chemical characteristics of geological formations. In groundwater investigations, resistivity measurements are widely used for distinguishing permeable aquifer formations from impermeable clay-rich layers because groundwater occurrence significantly affects conductivity and resistivity values. Clay formations generally exhibit relatively low resistivity due to their high moisture retention capacity and elevated ion concentration, whereas coarse-grained formations such as sand, gravel, and boulders saturated with freshwater display comparatively higher resistivity values. Variations in porosity and permeability also influence groundwater storage and movement within subsurface formations, thereby affecting measured resistivity responses. In the present study, resistivity interpretation involved detailed analysis of SN and LN log responses combined with lithological observations and SP measurements to identify productive groundwater-bearing zones and evaluate aquifer continuity. The interpretation process further considered formation saturation, sediment composition, and groundwater salinity conditions influencing subsurface electrical properties. The integration of multiple geophysical datasets improved interpretation accuracy and enabled reliable characterization of lithological boundaries and hydrogeological conditions within the study area. Therefore, resistivity interpretation formed a fundamental basis for identifying aquifer zones and assessing groundwater potential during the present investigation.

AI-Integrated Interpretation Framework

Artificial Intelligence concepts were integrated into the present hydrogeological investigation in order to improve geophysical interpretation accuracy, enhance aquifer prediction capability, and develop a modern framework for intelligent groundwater exploration. The AI-integrated interpretation framework involved systematic processing and analysis of geophysical logging data using machine learning concepts capable of identifying hidden relationships between formation resistivity and groundwater occurrence. The first stage of the framework involved data acquisition through geophysical logging measurements and detailed borehole lithological recording during drilling operations. These datasets included resistivity values, formation characteristics, lithological information, and hydrogeological observations collected at various depth intervals within the borehole. The second stage involved data preprocessing techniques including resistivity normalization, noise filtering, feature extraction, and organization of datasets into machine-readable formats suitable for AI-based analysis. The third stage included conceptual implementation of machine learning algorithms such as Artificial Neural Networks (ANN), Random Forest (RF), and Support Vector Machines (SVM) for automated lithological classification, aquifer identification, and groundwater prediction. These AI models possess the capability to analyze complex nonlinear relationships within geophysical datasets and generate predictive interpretations regarding groundwater occurrence and aquifer productivity. The final stage of the framework involved aquifer prediction and hydrogeological assessment through classification of permeable formations, impermeable layers, productive groundwater-bearing zones, and expected groundwater yield potential. The integration of AI concepts into geophysical investigations significantly improves interpretation efficiency, reduces uncertainty, enhances drilling success rates, and supports sustainable groundwater resource management. Therefore, the proposed AI-integrated framework represents an innovative approach for future hydrogeological investigations and groundwater exploration projects in semi-arid regions of Pakistan.

Subsurface Lithological Profile

The subsurface lithological profile interpreted from drilling observations and geophysical logging data revealed a highly heterogeneous sequence of alluvial and sedimentary formations extending to a total borehole depth of 515 feet (Table 1). The upper section of the borehole from 0–56 feet mainly consisted of dry clay mixed with sand deposits characterized by relatively low permeability and limited groundwater potential due to the dominance of fine-grained materials. Between depths of 56–82 feet, formations composed of sand and gravel were encountered, indicating moderate permeability and favorable groundwater movement conditions compared to overlying clay-rich layers. Clay formations observed between 82–89 feet and 108–141 feet acted as impermeable and confining layers restricting groundwater movement between adjacent permeable zones. Productive aquifer formations consisting of sand and gravel deposits were identified between 141–164 feet and 184–249 feet, representing favorable groundwater-bearing intervals with relatively high permeability and transmissivity characteristics. Another thick clay layer between 249–295 feet acted as an aquitard separating upper and deeper groundwater-bearing formations within the borehole profile.

The deeper section of the borehole revealed highly productive aquifer formations associated with coarse-grained sand, gravel, and boulder deposits extending between depths of 295–361 feet and 410–450 feet. These formations were interpreted as major groundwater reservoirs due to their high permeability, significant thickness, and interconnected pore spaces capable of storing and transmitting groundwater efficiently. Clay-rich formations between 361–410 feet and 450–460 feet functioned as confining layers restricting vertical groundwater movement and separating productive aquifers occurring at different depth intervals. Another water-bearing formation composed of sand, gravel, and sandstone deposits was identified between 460–480 feet, indicating additional groundwater potential within the deeper section of the borehole. The final section of the borehole extending from 480–515 feet mainly consisted of clay and shale formations characterized by low permeability and limited groundwater occurrence (Figure 3). Overall, the interpreted lithological profile demonstrated the presence of multiple productive aquifer zones separated by impermeable clay layers typical of alluvial depositional environments within the Potohar Plateau region. The identified coarse-grained formations possess favorable hydrogeological characteristics and indicate moderate to high groundwater potential suitable for long-term water supply development within the study area.

Results

Lithological Interpretation

The interpretation of geophysical well logging data revealed a highly heterogeneous subsurface lithological sequence consisting of alternating layers of clay, sand, gravel, boulders, sandstone, and shale formations within the investigated borehole profile. The upper and intermediate sections of the borehole were dominated by clay-rich formations characterized by relatively low resistivity values and limited permeability conditions, indicating poor groundwater movement and restricted water storage potential. In contrast, several coarse-grained formations composed of sand, gravel, and boulder deposits exhibited comparatively higher resistivity responses associated with freshwater saturation and enhanced groundwater occurrence. The lithological interpretation further demonstrated that impermeable clay layers acted as confining formations separating permeable groundwater-bearing zones occurring at different depth intervals within the borehole profile. Sandstone formations encountered within the deeper sections of the borehole also contributed to groundwater occurrence due to their moderate porosity and permeability characteristics. The interpretation of SN, LN, and SP logs enabled accurate delineation of lithological boundaries and improved understanding of subsurface hydrogeological conditions controlling groundwater movement and storage. The identified geological sequence reflects typical alluvial depositional environments commonly observed within semi-arid regions of the Potohar Plateau. The variation in lithological composition and formation thickness indicates complex sedimentary deposition processes that significantly influence groundwater distribution within the study area. The interpreted subsurface profile further confirmed the presence of multiple aquifer systems separated by confining clay layers, thereby creating favorable hydrogeological conditions for groundwater accumulation. Therefore, the lithological interpretation provided essential information for identifying productive aquifer zones and evaluating groundwater potential within the Khasala Service Area.

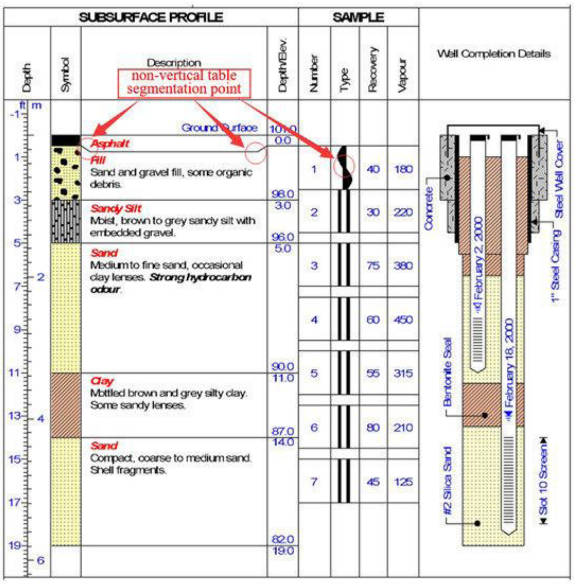

Figure 3: Interpreted lithological profile of the investigated borehole.

Identification of Aquifer Zones

Detailed analysis of geophysical logging data and lithological observations resulted in the identification of several productive groundwater-bearing aquifer zones occurring at different depths within the investigated borehole. The first productive aquifer zone was identified between depths of 141–164 feet and mainly consisted of permeable sand and gravel deposits possessing moderate groundwater storage potential and favorable hydraulic conductivity characteristics. The second aquifer zone extending from 184–249 feet was interpreted as a major groundwater-bearing formation composed predominantly of coarse-grained sand and gravel materials exhibiting relatively high permeability and transmissivity conditions. Another highly productive aquifer zone was encountered between depths of 295–361 feet where thick sequences of sand, gravel, and boulder deposits indicated excellent groundwater storage capacity and enhanced groundwater movement within interconnected pore spaces. The fourth productive aquifer zone identified between 410–450 feet also consisted of coarse-grained sand, gravel, and boulder formations characterized by favorable hydrogeological conditions suitable for groundwater extraction and long-term water supply development. Additionally, another water-bearing formation was encountered between depths of 460–480 feet where sand, gravel, and sandstone deposits exhibited moderate to good groundwater occurrence and permeability characteristics. The identified aquifer zones were separated by impermeable clay formations acting as confining layers restricting vertical groundwater movement and enhancing aquifer protection from surface contamination. The thickness, continuity, and lithological composition of the identified aquifers indicate significant groundwater storage potential within the study area. The integration of geophysical logs with drilling observations significantly improved the reliability of aquifer delineation and hydrogeological interpretation. Therefore, the identified aquifer zones represent important groundwater resources capable of supporting future municipal and commercial water supply requirements within the rapidly developing Rawalpindi Ring Road region.

Groundwater Potential

The hydrogeological investigation indicated that the deeper sand, gravel, and boulder formations possess highly favorable characteristics for groundwater occurrence, storage, and transmission within the study area. These coarse-grained formations exhibit relatively high porosity and permeability due to their larger grain size distribution and interconnected pore spaces, which facilitate efficient groundwater movement and accumulation within subsurface aquifers. The major groundwater-bearing zones identified during geophysical interpretation demonstrated significant aquifer thickness and lateral continuity, suggesting moderate to good groundwater potential suitable for sustainable groundwater extraction and water supply development. The deeper aquifer systems occurring between 295–361 feet and 410–450 feet were interpreted as the most productive groundwater reservoirs because of their extensive thickness, coarse sediment composition, and enhanced transmissivity characteristics. The presence of impermeable clay layers between productive aquifers further improves groundwater storage conditions by restricting vertical water movement and minimizing groundwater losses from permeable formations. Hydrogeological conditions observed within the study area are typical of layered alluvial aquifer systems where groundwater occurrence is strongly controlled by lithological heterogeneity and sediment permeability distribution. The groundwater potential assessment also indicated that the identified aquifers possess sufficient recharge and storage capacity to support future municipal and commercial groundwater utilization. Furthermore, the geophysical investigation demonstrated that the hydrogeological framework of the area is highly favorable for groundwater abstraction due to the occurrence of multiple productive aquifer horizons within the subsurface profile. The identified coarse-grained formations are expected to provide stable groundwater yields under controlled pumping conditions and sustainable extraction strategies. Therefore, the Khasala Service Area possesses moderate to good groundwater potential capable of supporting long-term water resource development associated with future infrastructural and urban expansion.

Estimated Groundwater Yield

The expected groundwater yield of the investigated borehole was estimated through detailed analysis of geophysical logging responses, lithological characteristics, aquifer thickness, and formation permeability conditions identified during the hydrogeological investigation. Based on the interpreted aquifer properties and observed geological conditions, the anticipated groundwater discharge from the borehole was estimated to range between 4000–5000 gallons per hour (gph), indicating moderate to high groundwater productivity within the study area. The deeper aquifer formations composed of sand, gravel, and boulder deposits contributed significantly to the estimated discharge capacity because these formations possess relatively high transmissivity and groundwater storage characteristics. The identified groundwater yield is considered suitable for commercial, municipal, and infrastructural water supply applications associated with future development projects along Rawalpindi Ring Road. The occurrence of multiple productive aquifer zones within the borehole profile further enhances groundwater extraction potential by allowing groundwater abstraction from different depth intervals depending upon operational requirements and pumping conditions. The estimated discharge also reflects favorable hydrogeological conditions associated with layered alluvial aquifer systems where coarse-grained permeable formations store and transmit groundwater efficiently. The interpretation of geophysical logging data enabled reliable estimation of groundwater productivity by correlating resistivity responses with formation permeability and groundwater saturation characteristics. However, the actual long-term groundwater yield may vary depending upon seasonal recharge conditions, pumping rates, aquifer connectivity, and groundwater management practices implemented within the region. The estimated discharge values nevertheless indicate that the investigated site possesses sufficient groundwater potential to support sustainable water extraction and future water supply development. Therefore, the hydrogeological investigation confirmed the suitability of the Khasala Service Area for groundwater development and commercial water supply utilization.

AI-Based Interpretation Outcomes

The conceptual integration of Artificial Intelligence into geophysical interpretation demonstrated significant potential for improving hydrogeological investigations, groundwater prediction, and aquifer characterization within the study area. AI-assisted interpretation techniques can enhance lithological classification accuracy by automatically analyzing geophysical logging data and identifying subtle relationships between resistivity values and subsurface geological formations that may not be easily recognized through conventional interpretation methods. Machine learning algorithms such as Artificial Neural Networks, Random Forest models, and Support Vector Machines possess the capability to process large geophysical datasets rapidly while reducing interpretation time and minimizing human-related analytical errors (Figure 4). AI-based interpretation further enables the identification of hidden aquifer patterns and complex nonlinear hydrogeological relationships associated with groundwater occurrence and formation permeability conditions. The integration of intelligent data processing techniques can significantly improve groundwater yield prediction accuracy by analyzing multiple hydrogeological variables simultaneously and generating predictive groundwater models for future exploration projects. AI-assisted systems can also support real-time drilling decisions by providing automated recommendations regarding drilling depth, aquifer targeting, and formation evaluation during groundwater exploration operations. Furthermore, AI integration reduces uncertainty in hydrogeological investigations by improving pattern recognition and enhancing predictive analysis capabilities associated with subsurface geological interpretation. The use of AI-based techniques additionally contributes to sustainable groundwater management through optimized groundwater exploration strategies, improved drilling efficiency, and reduced operational costs. The outcomes of the present study indicate that AI-assisted geophysical interpretation represents a highly promising approach for future groundwater exploration projects in Pakistan and other semi-arid regions experiencing increasing water scarcity and groundwater demand. Therefore, the integration of Artificial Intelligence with geophysical logging methods provides a modern and efficient framework for intelligent groundwater resource assessment and sustainable hydrogeological investigations.

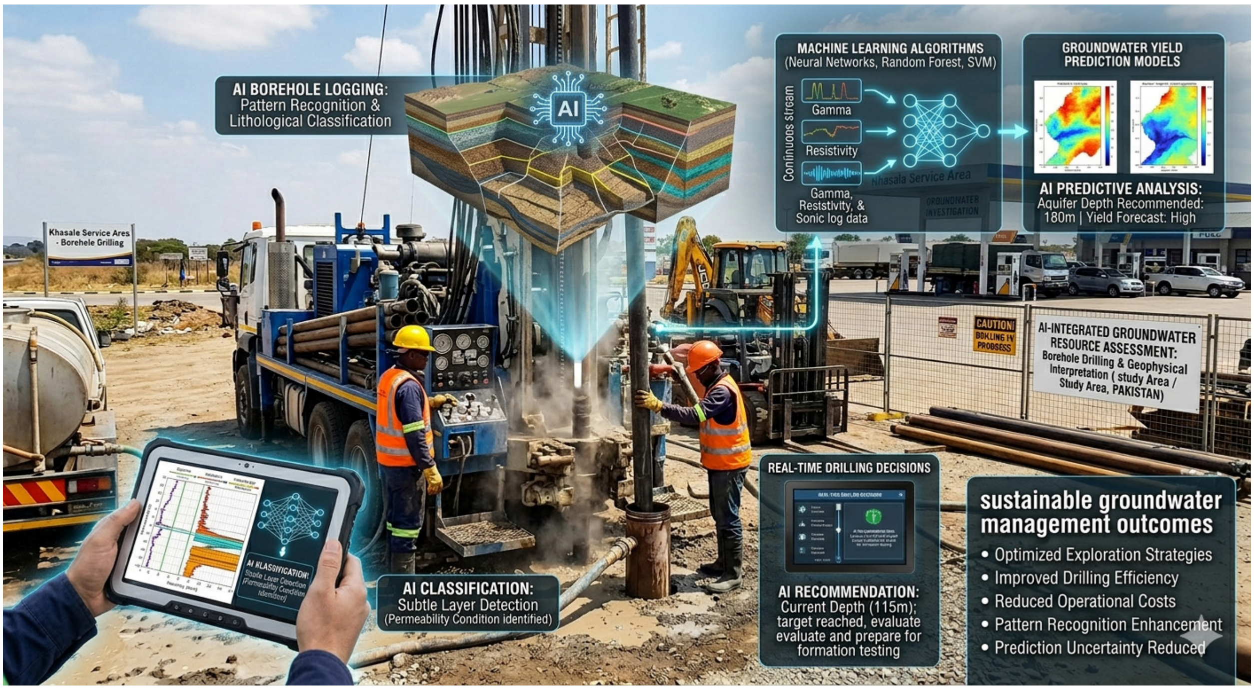

Figure 4: Proposed AI-integrated framework for groundwater exploration and geophysical interpretation.

Discussion

Hydrogeological Significance

The results of the present investigation indicate that the Khasala Service Area contains multiple productive groundwater-bearing aquifers separated by impermeable clay confining layers, thereby forming a layered aquifer system characteristic of alluvial depositional environments. Such hydrogeological conditions are commonly observed within semi-arid sedimentary basins where alternating sequences of permeable and impermeable formations control groundwater occurrence, movement, and storage within the subsurface environment (Table 2). The identified clay-rich formations act as confining units that restrict vertical groundwater movement and provide natural protection against contamination of deeper aquifers from surface pollutants and anthropogenic activities. The occurrence of several productive aquifer zones within different depth intervals further demonstrates the significant groundwater potential associated with coarse-grained sedimentary formations present in the study area [7]. The hydrogeological framework interpreted from geophysical logging and lithological analysis indicates favorable groundwater recharge and storage conditions within permeable sand, gravel, and boulder deposits. The layered aquifer system identified during the investigation also improves groundwater sustainability because groundwater extraction can be distributed across multiple aquifers depending upon pumping requirements and operational conditions [19]. Furthermore, the confining clay layers enhance groundwater retention and minimize rapid groundwater depletion within productive aquifer zones. The hydrogeological significance of the study lies in its ability to provide detailed subsurface information required for groundwater development, aquifer management, and future water supply planning within rapidly urbanizing regions [21]. The interpreted aquifer systems additionally represent important freshwater resources capable of supporting future municipal and commercial water demands associated with infrastructural expansion along Rawalpindi Ring Road. Therefore, the present investigation provides valuable hydrogeological insights regarding groundwater occurrence and aquifer distribution within the Potohar Plateau region.

Table 1: Subsurface Lithological Profile.

Depth Range (ft)	Lithology	Hydrogeological Interpretation
0–56	Dry clay + sand	Low permeability
56–82	Sand + gravel	Moderate permeability
82–89	Clay	Impermeable layer
89–108	Sand + gravel	Water-bearing formation
108–141	Clay	Confining layer
141–164	Sand + gravel	Productive aquifer
164–184	Clay	Impermeable formation
184–249	Sand + gravel	Major aquifer zone
249–295	Clay	Aquitard
295–361	Sand + gravel + boulder	High-yield aquifer
361–410	Clay	Confining formation
410–450	Sand + gravel + boulder	Productive aquifer
450–460	Clay	Impermeable layer
460–480	Sand + gravel + sandstone	Water-bearing formation
480–515	Clay + shale	Low permeability

Table 2: Identified Aquifer Zones and Hydrogeological Interpretation.

Aquifer Zone	Depth Range (ft)	Lithological Composition	Hydrogeological Interpretation
Zone 1	141–164	Sand + Gravel	Moderate permeability; local aquifer zone
Zone 2	184–249	Sand + Gravel	High permeability; major aquifer zone
Zone 3	295–361	Sand + Gravel + Boulder	Very high permeability; high-yield aquifer
Zone 4	410–450	Sand + Gravel + Boulder	Productive aquifer; good transmissivity
Zone 5	460–480	Sand + Gravel + Sandstone	Moderate aquifer; mixed lithology water-bearing zone

Importance of Coarse-Grained Formations

The coarse-grained sand, gravel, and boulder formations identified during the present investigation were interpreted as highly favorable groundwater-bearing formations due to their superior hydrogeological characteristics and groundwater storage capacity. These formations possess relatively high porosity resulting from larger grain sizes and interconnected pore spaces that facilitate efficient groundwater accumulation and movement within subsurface aquifers [3]. High permeability conditions observed within coarse-grained deposits enable rapid groundwater flow and improve aquifer transmissivity, thereby supporting sustainable groundwater extraction under pumping conditions. The identified boulder and gravel formations also exhibit enhanced groundwater recharge potential because water can infiltrate and migrate efficiently through permeable sedimentary layers. In contrast, clay-rich formations possess low permeability and restricted groundwater movement due to their fine-grained structure and compact sediment arrangement [15]. The occurrence of thick coarse-grained formations within deeper sections of the borehole significantly contributed to the moderate to high groundwater potential estimated for the study area. The transmissivity characteristics of these aquifers further indicate their suitability for long-term municipal and commercial water supply applications associated with urban development projects. Additionally, the hydrogeological properties of sand and gravel deposits improve groundwater storage efficiency and enhance aquifer productivity under continuous groundwater abstraction conditions [18]. The distribution and continuity of coarse-grained formations identified during the investigation also indicate favorable hydrogeological connectivity between productive aquifer zones within the study area. Therefore, the presence of extensive sand, gravel, and boulder formations represents one of the most important factors controlling groundwater occurrence and aquifer productivity within the investigated region.

Advantages of AI Integration

The integration of Artificial Intelligence into geophysical interpretation offers several significant advantages over conventional hydrogeological investigation methods by improving interpretation efficiency, predictive accuracy, and data analysis capability (Table 3). Traditional geophysical interpretation generally relies on manual analysis and expert judgment, which may introduce interpretation uncertainty and inconsistencies when dealing with complex geological conditions and large geophysical datasets. In contrast, AI-assisted interpretation enables automated analysis of resistivity logs and lithological information [21] through intelligent algorithms capable of identifying nonlinear relationships associated with groundwater occurrence and aquifer productivity. AI-based systems significantly reduce interpretation time by rapidly processing geophysical datasets and generating automated predictions regarding lithological classification and groundwater potential [2]. Furthermore, machine learning algorithms improve decision-making reliability by producing data-driven predictions rather than subjective interpretations based solely on human expertise. AI integration also enhances pattern recognition capability by identifying subtle hydrogeological trends and aquifer characteristics that may not be easily detectable through conventional interpretation approaches [8]. The ability of AI models to analyze multiple geological and geophysical variables simultaneously further improves groundwater yield estimation and aquifer prediction accuracy. AI-assisted interpretation additionally supports real-time drilling operations by providing immediate recommendations regarding drilling depth selection, aquifer targeting, and groundwater productivity assessment during exploration activities [23]. The application of AI in hydrogeological investigations also contributes to reduced operational costs, improved drilling success rates, and optimized groundwater exploration strategies. Therefore, Artificial Intelligence represents a transformative technological advancement capable of significantly improving groundwater investigations and sustainable water resource management practices.

Table 3: Advantages of AI-Assisted Groundwater Exploration [2,8,21,23].

No.	Aspect	Conventional Method	AI-Assisted Method
1	Data Interpretation	Manual and expert-based	Automated and data-driven
2	Processing Speed	Time-consuming	Rapid and efficient
3	Accuracy	Subject to human error	High predictive accuracy
4	Pattern Recognition	Limited capability	Detects complex nonlinear patterns
5	Aquifer Identification	Based on visual/log analysis	AI-based classification models
6	Groundwater Prediction	Approximate estimation	Model-based prediction
7	Decision Making	Subjective interpretation	Real-time intelligent support
8	Cost Efficiency	Higher operational cost	Reduced exploration cost
9	Drilling Success Rate	Moderate	Improved success probability
10	Data Handling	Limited multi-variable analysis	Handles large multi-source datasets efficiently

Sustainability Implications

The integration of Artificial Intelligence into groundwater exploration and hydrogeological investigations possesses significant implications for sustainable water resource management, particularly in semi-arid and water-stressed regions experiencing increasing groundwater demand. AI-assisted groundwater investigations can improve drilling success rates by accurately identifying productive aquifer zones and minimizing unsuccessful drilling operations associated with poor hydrogeological interpretation. The use of intelligent data analysis techniques further contributes to reduced exploration costs because AI systems can rapidly process large geophysical datasets and optimize groundwater exploration strategies more efficiently than conventional methods [24]. Sustainable groundwater extraction can also be improved through AI-based prediction models capable of estimating groundwater recharge conditions, aquifer productivity, and long-term groundwater availability under different pumping scenarios. AI-assisted hydrogeological systems additionally support long-term aquifer monitoring by continuously analyzing groundwater data and identifying changes in groundwater levels, water quality, and aquifer conditions over time. The integration of AI with geophysical investigations also enhances groundwater recharge assessment by improving understanding of hydrogeological connectivity and subsurface water movement within layered aquifer systems [16]. Furthermore, AI technologies can support groundwater management planning by providing predictive decision-support tools for sustainable pumping strategies and groundwater conservation practices. The application of intelligent hydrogeological frameworks is particularly important in rapidly urbanizing regions where groundwater resources are subjected to increasing extraction pressures and environmental stress [11]. AI-assisted groundwater investigations therefore represent an innovative approach for balancing water resource utilization with long-term aquifer sustainability and environmental protection objectives. Consequently, the integration of Artificial Intelligence into groundwater exploration has the potential to contribute substantially to sustainable water security and efficient groundwater management in Pakistan and other semi-arid regions.

Limitations of the Study

Despite the successful hydrogeological investigation and geophysical interpretation conducted during the present study, several limitations were identified that may influence the accuracy and generalization of the research findings. One important limitation involves the availability of limited digital geophysical

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datasets because the investigation primarily relied on borehole logging data collected from a single trial borehole within the study area. The absence of real-time Artificial Intelligence implementation and field-based machine learning applications also restricted the practical evaluation of AI-assisted hydrogeological interpretation during drilling operations. Another limitation of the study was the lack of long-term pumping test analysis required for detailed assessment of aquifer transmissivity, storage coefficients, and sustainable groundwater yield under prolonged extraction conditions. Additionally, the regional hydrogeological database available for the study area was limited, thereby restricting large-scale hydrogeological correlation and regional groundwater modeling capabilities. Variations in seasonal recharge conditions, groundwater abstraction rates, and climatic factors may further influence groundwater availability and aquifer productivity beyond the conditions interpreted during the present investigation. The study also focused primarily on resistivity-based geophysical logging methods and did not integrate additional geophysical techniques such as seismic surveys or electromagnetic investigations that could further improve subsurface characterization accuracy. Furthermore, the conceptual AI framework proposed in the study requires validation through field-scale implementation using large hydrogeological datasets and advanced machine learning algorithms. Future studies should therefore integrate Geographic Information Systems (GIS), remote sensing technologies, deep learning approaches, and regional hydrogeological databases for more comprehensive groundwater prediction and aquifer assessment. Consequently, addressing these limitations in future research will significantly improve the accuracy, reliability, and practical application of AI-assisted groundwater exploration frameworks.

Proposed AI Framework for Future Groundwater Studies

The present study proposes a comprehensive Artificial Intelligence-integrated framework for future groundwater investigations aimed at improving hydrogeological interpretation, aquifer prediction, and sustainable groundwater management practices in semi-arid regions. The first phase of the proposed framework involves systematic data collection through borehole geophysical logging, resistivity surveys, pumping tests, groundwater monitoring, and GIS-based hydrogeological mapping. These datasets should include lithological information, resistivity measurements, groundwater levels, aquifer properties, and remote sensing observations required for advanced hydrogeological analysis and predictive modeling. The second phase focuses on data preprocessing techniques including signal filtering, noise reduction, resistivity normalization, feature extraction, and preparation of machine-readable hydrogeological datasets suitable for Artificial Intelligence applications. The third phase involves implementation of AI modeling approaches through neural network training, Random Forest classification, deep learning algorithms, and predictive machine learning models capable of identifying groundwater-bearing formations and estimating aquifer productivity. The fourth phase includes groundwater prediction and hydrogeological assessment involving aquifer mapping, groundwater yield estimation, groundwater recharge analysis, and contamination risk evaluation using intelligent predictive systems. The final phase of the framework involves decision-support applications including optimal drilling depth selection, sustainable pumping strategy development, groundwater management planning, and long-term aquifer monitoring supported by AI-assisted analytical tools. The integration of AI, GIS, remote sensing, and hydrogeophysical datasets within a unified framework significantly improves groundwater exploration efficiency and predictive reliability. Furthermore, the proposed framework supports sustainable groundwater management by enabling real-time hydrogeological analysis, intelligent decision-making, and optimized groundwater utilization strategies. Therefore, the proposed AI-integrated framework provides a modern scientific approach for future groundwater investigations and water resource management in Pakistan and other groundwater-stressed regions.

Conclusion

The present study successfully investigated groundwater potential at the Khasala Service Area along Rawalpindi Ring Road through detailed geophysical well logging integrated with Artificial Intelligence-based interpretation concepts for sustainable groundwater exploration and hydrogeological assessment. The borehole investigation revealed complex subsurface lithological conditions consisting of alternating sequences of clay, sand, gravel, boulders, sandstone, and shale formations extending to a total depth of 515 feet within the investigated area. Detailed interpretation of Short Normal, Long Normal, and Spontaneous Potential geophysical logs enabled the identification of multiple productive aquifer zones occurring between depths of 141–164 feet, 184–249 feet, 295–361 feet, 410–450 feet, and 460–480 feet. These aquifer zones mainly consisted of coarse-grained sand, gravel, and boulder formations possessing favorable hydrogeological characteristics including high permeability, good transmissivity, and efficient groundwater storage potential. Based on lithological interpretation and geophysical analysis, the expected groundwater discharge was estimated between 4000–5000 gallons per hour, indicating that the study area possesses moderate to high groundwater potential suitable for commercial and municipal water supply development. The investigation further demonstrated that Artificial Intelligence can significantly improve geophysical interpretation by enhancing lithological classification accuracy, identifying hidden aquifer patterns, reducing interpretation uncertainty, and improving groundwater yield prediction. AI-assisted hydrogeological analysis additionally offers major advantages including automated data processing, intelligent predictive modeling, rapid interpretation capability, and real-time decision support during groundwater exploration operations. The study therefore highlights the importance of integrating modern AI technologies with conventional geophysical techniques for improving groundwater investigations and sustainable aquifer management. Overall, the integration of Artificial Intelligence with geophysical logging provides an innovative, efficient, and sustainable framework for groundwater exploration in Pakistan and other semi-arid regions experiencing increasing groundwater demand and water resource challenges.

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Recommendations

Based on the findings and hydrogeological interpretation of the present study, several recommendations are proposed for improving future groundwater investigations and sustainable groundwater resource management practices within the study area and other semi-arid regions. Future groundwater exploration projects should integrate Artificial Intelligence-assisted interpretation techniques with conventional geophysical logging methods in order to improve lithological classification accuracy, aquifer prediction reliability, and groundwater yield estimation. Regional hydrogeological databases containing geophysical logs, pumping test results, groundwater levels, lithological records, and remote sensing information should be developed to support machine learning applications and large-scale hydrogeological modeling activities. Long-term pumping tests and groundwater monitoring programs should also be conducted to evaluate aquifer transmissivity, storage coefficients, groundwater recharge conditions, and sustainable groundwater extraction limits under prolonged pumping conditions. The integration of Geographic Information Systems, remote sensing technologies, and deep learning algorithms is further recommended for advanced groundwater potential mapping, aquifer delineation, and groundwater contamination assessment within rapidly developing urban regions. Sustainable groundwater monitoring systems should additionally be established to continuously assess groundwater levels, water quality conditions, and aquifer behavior under changing environmental and climatic conditions. Interdisciplinary collaboration between hydrogeologists, geophysicists, data scientists, and Artificial Intelligence researchers should be promoted in order to develop innovative groundwater exploration frameworks and intelligent hydrogeological decision-support systems. Government agencies and water resource management organizations should further encourage the adoption of AI-assisted hydrogeological technologies for improving groundwater planning and sustainable water resource utilization. Therefore, the implementation of these recommendations will significantly enhance groundwater exploration efficiency, improve groundwater management practices, and support long-term water security within Pakistan and other groundwater-stressed regions.

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Conflict of Interest

Authors declare that they have no conflict of interest with this publication.

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